Strategies for Promoting Resilience to Increased Coastal Flooding Along the Downtown Boston Waterfront

Interactive Qualifying Project
SZT 1301

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Abstract

Rising sea levels and increased storm severity, due to climate change, are affecting coastal cities around the world. Sea levels in Boston are projected to rise six feet by 2100, and storm severity is also projected to increase. These two factors are increasing the risk of flood damage in the Downtown Boston area. Our team conducted vulnerability assessments at five sites along the waterfront in Downtown Boston to understand the risk of flooding. To address the vulnerabilities, we presented resilience strategy recommendations to the Boston Redevelopment Authority in their efforts to revise the Municipal Harbor Plan.

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The Boston Harbor Association

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Attendees of our Expert Review Panel

- Scott Bishop, STOSS Landscape Architecture
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- Chris Watson, University of Massachusetts- Boston

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- Nicholas Pace, Coast Guard Building
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Executive Summary

Greenhouse gases, largely from anthropogenic sources, are causing an increase in global temperatures (TBHA, 2013). Temperature increase leads to the thermal expansion of water as oceans are heated and the melting of polar ice caps (EPA, 2013). Changing temperatures also affect the location and amount of precipitation that falls, often increasing the severity of storms. The northeast region of the United States is expected to see a sharp increase in precipitation (EPA, 2010). The combination of rising temperatures and increasing precipitation is leading to global sea level rise, and in Boston sea levels are projected to rise two feet by the year 2050 and six feet by the year 2100 (TBHA, 2013).

In order to address flooding caused by sea level rise, a variety of resistance and resilience strategies can be implemented. Resistance strategies actively prevent water from entering buildings and surrounding areas. Resilience strategies are used to reduce structural damage; however, these strategies do not prevent water from entering a building (Bloch, 2012). These forms of strategies can be applied specifically to a building site or an entire neighborhood. Depending on the risk of the site, short-term and long-term strategies are applied in order to protect the study area from flooding.

In February 2013, The Boston Harbor Association published their report *Preparing for the Rising Tide*, in which they assessed the vulnerability of the buildings along the Downtown Boston waterfront to flooding caused by climate change. The report provides resilience strategy recommendations for reducing the risk of flood damage in the buildings of the study area. Our group continued upon this research by assessing the vulnerability of the rest of the buildings in the study area and provided flood resilience strategy recommendations to be used both on-site and in the general neighborhood. We assessed the James Hook Lobster Company, the area surrounding the Coast Guard Building, the Rowes Wharf Complex, the Harbor Towers, and the Christopher Columbus Park, shown in Figure ES-1.

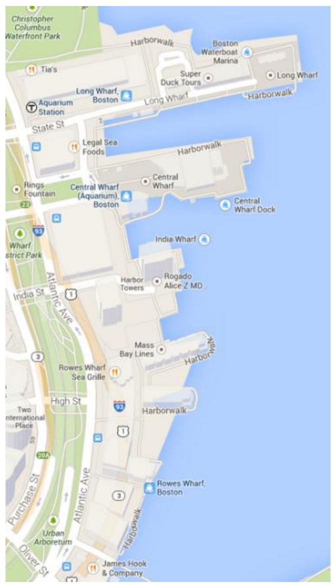

Figure ES-1: Map of the study area (*Google Maps*)

We then presented our findings and recommendations to the Boston Redevelopment Authority to be included in the Municipal Harbor Plan. The Municipal Harbor Plan is a two-year project focused on effectively reorganizing and protecting the Downtown Boston waterfront against climate change (BRA, 2013). Our project goal and objectives were as follows.

Goal: Determine the vulnerability of the harbor waterfront in Downtown Boston to sea level rise and storm surge and provide recommendations to the Boston Redevelopment Authority on strategies to increase resiliency against those threats.

- **Objective 1:** Assess the vulnerability of buildings to sea level rise and storm surge in the study area not previously assessed by TBHA.
- **Objective 2:** Identify strategies to increase resiliency that have been proposed or implemented in other cities and assess their strengths, weaknesses, and feasibilities.
- **Objective 3:** Gather expert feedback on strategies to increase resiliency that can be applied to the study area and present them to the Boston Redevelopment Authority.

Methodology

To complete our first objective and assess the vulnerabilities of the buildings, we identified critical components in the five locations by talking with building managers and viewing site plans. We used surveying equipment and a benchmark of a known elevation on the southwest corner of the Coast Guard Building to measure the critical elevations of these components. Our calculated error of closure ranged from 0.014 ft to 0.071 ft.

We took measurements in terms of the North American Vertical Datum of 1988 (NAVD 88), which is a vertical measurement in relation to a single point of origin on the continent (TBHA, 2013). Boston's average high tide is 4.8 ft NAVD, today's 100-year storm is 9.8 ft NAVD, and the projected 100-year storm in 2100 is 12.3 ft NAVD. After taking our measurements, we created a scale to define the vulnerability of components of buildings in our study area.

- **High vulnerability:** less than 10 ft NAVD can be affected by today's high tide, today's annual storm, or today's 100-year storm

- **Moderate vulnerability:** between 10 and 14 ft NAVD can be affected by flooding within the next century
- **Low vulnerability:** higher than 14 ft NAVD may not be affected within the next century

We also considered how severe the consequences could be if a specific component was damaged by flooding. We used the chart in Table ES-1 to assess the risk of each building site in our study area. Risk is a function of the likelihood of an event occurring and the magnitude of potential consequences. Table ES-1 defines the levels of risk as high, moderate, and low (ICF International, 2009). We completed more accurate risk assessments for these buildings because we considered vulnerability and the magnitude of the consequences. This allowed us to make more appropriate recommendations for resilience strategies.

Likelihood	**Consequence**				
	1.Catastrophic	**2.Major**	**3.Moderate**	**4.Minor**	5.Insignificant
A. Very likely	1A	2A	3A	4A	5A
B. Likely	1B	2B	3B	4B	5B
C. Medium	1C	2C	3C	4C	5C
D. Unlikely	1D	2D	3D	4D	5D
E. Very unlikely	1E	2E	3E	4E	5E

Table ES-1: Qualitative evaluation of likelihood and consequence of hazardous events (ICF International, 2009)

To accomplish our second objective, we researched flood resilience strategies being used in coastal cities around the world that could possibly be implemented in Boston. We read and evaluated the following reports:

- Julie Wormser's *Living with Water* provided case studies of successful strategies used in coastal cities around the world (J. Wormser, personal communication, September 4, 2013).
- The Green Ribbon Commission's *Building Resilience in Boston* provided recommendations that Boston building owners should apply to their buildings to reduce damage from flooding (Green Ribbon Commission, 2013).
- The City of Boston's *Municipal Harbor Plan* gave recommendations for the types of strategies that should be applied in the Downtown Boston waterfront (BRA, 2013).
- The Boston Harbor Association's *Preparing for the Rising Tide* recommended strategies for buildings in Downtown Boston (TBHA, 2013).
- Case studies of resilience strategies from around the world compiled by Crystal Aiken from TBHA provided preliminary ideas about several more strategies for flood resilience that have been implemented in urban coastal areas (C. Aiken, personal communication, September 12, 2013).

We chose these reports because they contained information on resilience strategies proposed by experts and ideas of successful, creative solutions that other coastal cities have implemented. We compiled a list of both short- and long-term strategies as well as site-specific strategies to be applied directly to buildings and neighborhood strategies to be applied to the general area. We then identified strategies that have high potential for reducing vulnerabilities and risks from flooding. In our recommendations, we applied strategies to the five building sites in our study area and the general neighborhood based on our critical elevation measurements. Some of the strategies we identified are as follows:

Short-Term Strategies

- **Emergency preparedness strategies**: This consists of supplies and actions that building managers plan for their buildings during severe weather and flooding.
- **Flood sealants and shields**: Flood sealants are waterproof coatings and injections that can seal openings in buildings. Flood shields are barriers that can be placed around openings to stop water from entering windows and doors.
- **Backflow valves for sewage management**: Valves can be installed to prevent the backup of sewage during high water levels.
- **Improved building materials**: These building materials are water resistant to protect different aspects of buildings from significant water damage.
- **French drains**: These fairly inexpensive drains divert water from buildings to a different location.
- **Increasing vegetation**: Vegetation can reduce the effects of storm surge and provide minor absorbance effects of water.

Long-Term Strategies

- **Breakaway walls:** These walls are not part of the structural supports of buildings, which collapse when put under pressure from flooding and storms.

- **Raised roads**: Raising roads can protect important travel routes during flooding and help divert water away from buildings.
- **Floodable developments**: The use of garages or cisterns diverts excess water during storm events.
- **Retention ponds**: Public spaces can be converted into water collection spaces during storm events.
- **Rain gardens**: Areas of vegetation can infiltrate storm water back into the soil to reduce flooding.
- **Drainage systems and permeable pavement**: Expanding drainage systems can aid cities in handling large amounts of floodwater. Permeable pavement is specially designed pavement that allows water to flow through it, so that the water is filtered and can safely enter city drains.
- **Elevation strategies**: All buildings can raise their critical service equipment to higher levels than the bottom floor. Buildings may also consider moving important rooms and inventory above the first floor. A more drastic, but potentially very beneficial idea is to raise buildings above flood levels. Some buildings can also temporarily be raised through the use of flotation devices.
- **Living shorelines**: Wetlands and biological habitats have beneficial ecological effects and can protect shorelines from erosion and storm surge.

After compiling our list of strategies, we presented our ideas to a panel of experts for review. The expert review panel provided valuable feedback on our recommendations, and we made revisions where suggested. We then compiled our suggestions into a memo to be presented to the Boston Redevelopment Authority for inclusion in the Municipal Harbor Plan.

Findings and Recommendations

Using the vulnerability assessments, we identified strategies to be applied to the five sites in our study area. In this section we will discuss our findings and recommendations regarding short- and long-term strategies, followed by our recommendations for each specific site and for the general neighborhood. We then present our findings and recommendations for the potential negative impacts of these strategies and future research that will be necessary for this topic.

Short- and Long-Term Strategies

We found that building specific strategies can be effective in increasing resiliency in both the short and long term. Examples of these strategies are:

Short-Term Strategies

- Create emergency preparedness plans
- Add flood sealants
- Install flood shields

Long-Term Strategies

- Raise critical equipment
- Improve building materials
- Raise seawalls

Short-term strategies can be implemented now for buildings that are at risk of flooding due to today's 100-year storm. Long-term strategies can be implemented in the future as sea levels continue to rise and buildings become more at risk. We recommend that these strategies be applied according to the risk of the site. Our recommendations for the five sites that we studied are as follows.

James Hook Lobster Company: The original James Hook Lobster Company building burned down in 2008, resulting in the construction of a temporary building on the same site. From our surveying measurements, we determined James Hook Lobster Company to be at low to moderate vulnerability to flooding. The consequences of flooding could be moderate since it is a temporary structure. The current building could be damaged by flooding, disrupting the daily operations for this business. Overall, it is at a moderate risk due to flooding. In order to reduce this risk, we recommend the following:

- Create emergency preparedness plans
- Apply flood sealants
- Install flood shields

The Coast Guard Building: This homeland security building was built in 1918 and was renovated in 1980 (Emporis, 2013). From our measurements, we found that the critical equipment of the Coast Guard Building is at low to moderate vulnerability to flooding. There are major consequences of flooding due to the importance of the outdoor service equipment, including the HVAC and electrical systems. If this service equipment was damaged, there could be a disruption in the operation of this homeland security building. Overall, it is at high risk due to flooding. Our recommendations for the Coast Guard Building are as follows:

- Create emergency preparedness plans
- Apply flood sealants
- Raise the seawall
- Raise or relocate HVAC and electrical systems

Rowes Wharf Complex: This historical wharf was originally built in 1764 for industrial water traffic into the Harbor. It was heavily renovated in 1987, becoming the "Gateway to Boston" (A View on Cities, 2010). From our measurements, we found that the components of the Rowes Wharf Complex are at low to high vulnerability. There is a grate located outside the garage leading directly to the generator and other underground service equipment. Due to the location of the critical equipment in this building, flooding could have major consequences. If this equipment was damaged, guests and residents could be negatively affected. Overall, it is at high risk due to flooding. In order to reduce the risk of flooding, we recommend the following:

- Raise the seawall
- Raise dock posts
- Relocate or raise all critical equipment
- Cover and divert water from vent
- Install permeable pavement

Harbor Towers: These two 40 story residential condominiums were built in 1971 and contain 624 units (TBHA & BRA, 2013). Through surveying, we found all measured components of the

Harbor Towers to be at either moderate or high vulnerability to flooding. The service equipment for both buildings is located in the basement, and both buildings have experienced water damage due to flooding. Due to the location of critical equipment in these buildings, flood damage to this equipment could be disruptive to the residents. Overall, it is at high risk due to flooding. In order to reduce the risk of flooding at the Harbor Towers, we recommend the following.

- Create emergency preparedness plans
- Raise seawalls
- Seal the basement and waterproof the concrete
- Relocate or raise service equipment
- Raise the outdoor outlets
- Install French drains

Christopher Columbus Park: Boston's first waterfront park was opened in 1976, and renovations were made in 2003 (TBHA & BRA, 2013). Unlike other building sites, Christopher Columbus Park was measured as a public open space with potential for implementing certain resilience strategies. From our measurements, we found the electrical box and the seawall to be at high vulnerability to flooding, but the consequences of flooding could be minor. The park does not contain much critical equipment and is mainly used as an open public space for recreation. Overall, the park is at low risk due to flooding. In order to reduce this minimal risk, we recommend the following.

- Raise the seawall
- Move or raise the electrical equipment
- Install a rain garden or retention pond

- Lower the drains on the walkway
- Install permeable pavement

Neighborhood Strategies: In the long-term, the topography of Boston will need to be changed in order to increase resiliency to flooding. Some areas will need to be purposefully raised or lowered in order to protect critical equipment. We recommend a combination of the following strategies to be applied to the general neighborhood of Downtown Boston.

- Create below-grade public space
- Improve drainage systems
- Raise and slope roads
- Create living shorelines, beach nourishment, levees and dikes
- Construct underground water storage

Negative Impacts

We found that implementing resilience strategies can have a variety of unintended negative impacts. These impacts can be categorized as follows:

- **Negative impacts on aesthetics:** Strategies with a negative impact on the aesthetics of the area will be less desirable for the community. An example of this is raising a seawall because it obstructs the view of the ocean. We recommend that research be done on public opinion of strategies before implementation to successfully increase the resiliency of the area while still maintaining the scenic attraction.
- **Degradation of materials:** Certain strategies may be difficult to implement due to the materials that they require. Since salt water is highly corrosive, materials such as concrete

used in seawalls will be worn down over time if they are not consistently coated with a water-resistant sealant. This would require additional upkeep, and the seawalls would need to be repaired or replaced if they were not kept correctly. Before implementing a strategy, we recommend that research be done on the most effective building materials.

- **Negative financial impacts:** Some strategies, such as creating underground water storage, could be very costly and could possibly put financial strain on the community. We recommend that a detailed cost analysis be done before implementing a strategy, and it will be necessary to determine where funding is coming from.
- **Negative impacts on surrounding areas:** Some structures can have a positive impact on the immediate surrounding area, while having a negative impact on other areas. For example, a seawall can protect the building that it is in front of, but this could cause water to flood surrounding areas. We recommend that all possible strategy impacts be studied and understood before implementation.
- **Long timetables for communities:** Implementing some strategies would take a long period of time, and this could be undesirable for the community. For example, an underground water storage facility would be under construction for a long period of time. We recommend that the timeline of implementing strategies along with public opinion of that timeline be understood before implementation.

Future Considerations

Due to limitations in our research, we recommend future researchers elaborate on the material in the following areas.

- We only examined our study area of Downtown Boston, so we were unable to model how our recommendations could affect the surrounding neighborhoods. We recommend that future researchers examine Boston as a whole in order to provide the most effective resilience strategy recommendations.
- To make our recommendations, we only used sea level rise and storm severity predictions with static water levels that did not account for wind or wave action. We recommend that future researchers take these factors into account in order to give a more accurate timeline on when resilience strategies should be implemented.
- We were unable to gain access to the Coast Guard Building, so we could only conduct a limited vulnerability assessment. We recommend that future researchers obtain more information on the building and conduct a more thorough assessment.
- We based the cost estimates of our recommended strategies on similar projects, so the feasibility of our suggestions is limited. We recommend that future researchers conduct assessments on each individual building in order to obtain more accurate figures.

Conclusion

Sea level rise and increased storm severity due to climate change pose serious threats to the Boston Harbor. The Downtown Boston area must prepare for these problems from both building-specific and neighborhood levels. For our project, we determined the vulnerability of the remaining buildings in the Downtown Boston area, not previously completed in *Preparing for the Rising Tide*. We then researched and made recommendations for strategies to be applied to specific buildings and the entire area to increase resiliency. These recommendations were given to the Boston Redevelopment Authority in their efforts to revise the Municipal Harbor Plan.

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2.2	Stephanie Lindow	Stephanie Lindow, Kirk Murphy
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3- Methodology		
3.1	Kelly Knopp	Kelly Knopp, Jonah Rosch
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3.3	Stephanie Lindow, Jonah Rosch	Kelly Knopp, Jonah Rosch
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(1-5)	Jonah Rosch	Kelly Knopp, Kirk Murphy
(6-7)	Kirk Murphy	Kelly Knopp, Stephanie Lindow, Jonah Rosch
(8)	Stephanie Lindow	Kelly Knopp, Kirk Murphy
5- Recommendations & Conclusions	Kelly Knopp	Jonah Rosch
Appendix A	Kelly Knopp, Stephanie Lindow, Jonah Rosch	All
Appendix B	Stephanie Lindow	All
Appendix C	Jonah Rosch	All
Appendix D	All	All

Table of Contents

List of Figures

List of Tables

1) Introduction

Climate change is creating harmful repercussions, such as sea level rise and rapid changes in weather patterns, all across the planet. According to the Intergovernmental Panel on Climate Change (IPCC), this increase in greenhouse gas concentrations is due to human activity, processes such as fossil fuel combustion, and industries such as cement production (IPCC, 2013). Today, concentrations of these gases in ice cores are at the highest point in over 800,000 years (IPCC, 2013). A consequence of this increase in greenhouse gas emissions is the increase in global temperatures (IPCC, 2013). The increase of global temperatures causes the melting of ice caps and the thermal expansion of water, raising global ocean levels. Warmer temperatures also cause increased water evaporation into the atmosphere, creating shifts in air and ocean currents that lead to changing weather patterns. Experts believe that this is increasing the severity of storms (Shah, 2012). Rising sea levels and increasing storm severity are putting more coastal communities at risk for flooding.

Increased flooding can have negative impacts on coastal cities. It can result in damaged property, health and ecological problems, social problems, and billions of dollars in repair costs (Sims, 2012). For example, coastal cities that endured Superstorm Sandy experienced severe structural, economic, and social damages (TBHA, 2013). Superstorm Sandy was a storm of a magnitude only expected to occur every 100 years. The superstorm hit New York City during high tide with rain and winds up to 80 miles per hour, leading to severe flooding and destruction of property (Newman, 2012).

The coastal city of Boston, Massachusetts, was fortunate that Superstorm Sandy occurred during low tide, which limited the damage. However, current models predict that Boston will experience two feet of sea level rise by the year 2050 and possibly six feet by the year 2100 with increasing storm severity (TBHA, 2013). Boston has not yet experienced severe consequences due to rising sea levels and increased storm severity, but the city must begin to take measures to reduce future risks.

The US Global Change Research Program presents two general strategies for areas that are currently at risk, or have potential risks for flooding in the future. The first is mitigation, which is "an intervention to reduce the sources or enhance the sinks of greenhouse gases and other climate warming agents" (USGCRP, 2013). An example of mitigation is an effort to reduce car emissions. The second strategy is adaptation, "an adjustment in natural and/or human systems to a new or changing environment that exploits beneficial opportunities and moderates negative impacts" (USGCRP, 2013). An example of adaptation would be improving seawalls along the coast to help protect coastal infrastructure. Mitigation and adaptation strategies together can allow us to reduce the risks of rising sea levels and increased storm severity.

The City of Boston has been working on mitigation strategies to reduce greenhouse gas emissions throughout the city. Mayor Menino created the Climate Action Leadership Committee and the Community Advisory Committee in 2009 (City of Boston, 2011). He proposed that the two committees produce the following:

- Goals to reduce greenhouse gas emissions within the community
- Strategies to allow for Boston to address climate change effects

- Reasonable procedures to distribute the benefits and financial responsibilities of these strategies

Following these calls for more work to protect Boston from the impacts of climate change, the Boston Redevelopment Authority (BRA) is currently revising the Municipal Harbor Plan for Downtown Boston. This potential two-year plan is working to commence redevelopment for Boston in order to accommodate the city for sea level rise. The study area of this plan lies between the Christopher Columbus Park to the north and Fort Point Channel to the south. To raise awareness for these climate change issues and to begin to prepare Boston for these changes, The Boston Harbor Association (TBHA) recently released the report, *Preparing for the Rising Tide*. In contrast to other proposals for the City of Boston that focus on resistance, this report emphasizes resilience strategies, which are strategies that do not actively prevent water from entering the city, but rather limit the damage caused by flooding. This report contains vulnerability assessments in Downtown Boston and recommendations for adaptation strategies to reduce damage from flooding. In order to further protect Boston from the risks associated with flooding, it was necessary to expand upon the research done in this report.

The goal of our project was to develop recommendations for the BRA containing flood resilience strategies to Downtown Boston at sites that were not assessed in TBHA's report. To assist TBHA, and ultimately the BRA's Municipal Harbor Plan, our project team continued the research from *Preparing for the Rising Tide* for Downtown Boston. To achieve this goal, we completed three objectives. For our first objective, we conducted vulnerability assessments on buildings in the Downtown Boston study area that were not included in *Preparing for the Rising*

Tide. We measured critical flood elevations, with surveying equipment, for the following five sites and the surrounding neighborhood.

- James Hook Lobster Company
- Captain John Foster Williams Coast Guard Building
- Rowes Wharf Complex
- Harbor Towers
- Christopher Columbus Park

For our second objective, we identified resilience strategies from around the world. We made recommendations for where these strategies could be applied in our study area based on our vulnerability assessments. For our third objective, we held a review panel of experts to present our recommendations and receive feedback. We made the suggested changes and presented our strategies to the Boston Redevelopment Authority in memo form. Our proposed recommendations were mainly focused on building specific and neighborhood levels, and we revised them according to suggestions made by our expert review panel. We developed short-term and long-term resilience strategies for each building, along with resilience strategies for the Downtown Boston neighborhood. An example of a short-term strategy for a building is installing a flood shield, and an example of a long-term strategy is moving service equipment to a higher location.

Through this project, we hope that our data and proposed recommendations assist the BRA in their revision of the Municipal Harbor Plan. Even though our recommendations in this report are focused on the Downtown Boston area, rising sea levels and increased storm severity are global problems and these recommendations could be applied to similar coastal cities.

2) Background

Rising sea levels and more severe storms, caused by climate change, are increasing the likelihood and severity of coastal flooding damage across the globe. According to The Boston Harbor Association, there is a need for coastal cities to “be prepared for the likely events of tomorrow” (TBHA, 2013). The need to increase the resiliency of Downtown Boston against flooding is an important issue, which is currently being addressed in the Boston Redevelopment Authority’s revision of the Municipal Harbor Plan. We begin this chapter with an explanation of the causes and impacts of climate change. We then focus on various consequences that flooding poses to coastal cities, particularly Boston. We conclude this chapter by introducing information on resilience strategies that could potentially be implemented in Downtown Boston.

2.1) Causes and Consequences of Climate Change

Greenhouse gases are increasing the overall temperature of the planet, leading to the rise of global sea levels and changes in weather patterns (IPCC, 2012). The consequences of climate change are affecting the entire planet. Many cities, including Boston, are beginning to address this threat.

2.1.1) Evidence for Climate Change

A main indicator for global climate change is the general trend of rising global surface temperatures. While there are fluctuations of temperature on a year-to-year basis, the general trend is an increase (EPA, 2010). Global surface temperatures have been recorded since the

1880s. Since then, the average global surface temperature has increased by 1.4^{o}F (EPA, 2010). There has also been a sharp increase in temperatures since the 1940s, when activities using fossil fuels produced more greenhouse gases. As of 2011, the 20 warmest years on record have all occurred since 1981 and the 10 warmest have occurred since 1999 (NOAA, 2011).

The root cause of climate change is the increase in carbon dioxide and other greenhouse gases in the atmosphere. Studies show that the overall energy output from the sun has not increased since the 1700s, showing that the rise in global temperatures has been caused by human involvement (NOAA, 2011). Carbon dioxide, the greenhouse gas most responsible for warming effects, has varied between 170 parts per million (ppm) and 300 ppm over the last 800,000 years. However, the concentration of carbon dioxide has increased by 35% since 1760, the start of the industrial revolution (NOAA, 2011). Figure 1 illustrates the positive correlation between global temperature and carbon dioxide concentration starting in the 1940's. Factors such as the burning of fossil fuels and deforestation have led to this sharp increase in CO_2 emissions (EPA, 2010). The current concentration of CO_2 in the atmosphere is 397 ppm (Earth's CO2 Homepage, 2013). Models predict that it could increase by 1.5% between 2005 and 2020 (EPA, 2010). The increase in CO_2 emissions is clear evidence for human involvement in climate change.

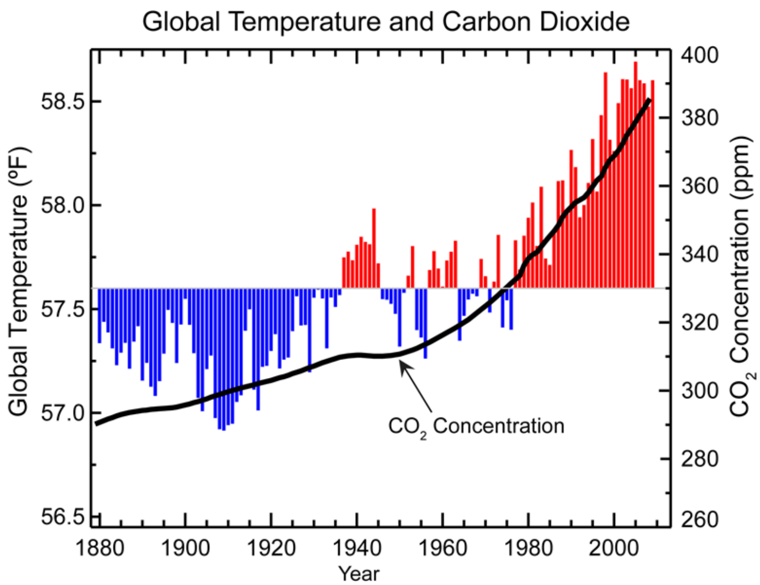


Figure 1: Graph showing the sharp increase in average temperature and carbon dioxide concentrations since the 1940s (NOAA, 2011)

2.1.2) Consequences of Climate Change

The increase in global surface temperature, caused by greenhouse gases, creates a number of impacts on the planet (Greenhouse Gas Emissions, 2010). Figure 2 illustrates the distribution of heat changes on Earth between the land, atmosphere, ice, and the ocean since 1961. Evident in recent years, about 90% of the heat produced by global warming is absorbed into the ocean (Shah, 2012). This increase in global temperatures has two main consequences: sea level rise and changes in precipitation patterns.

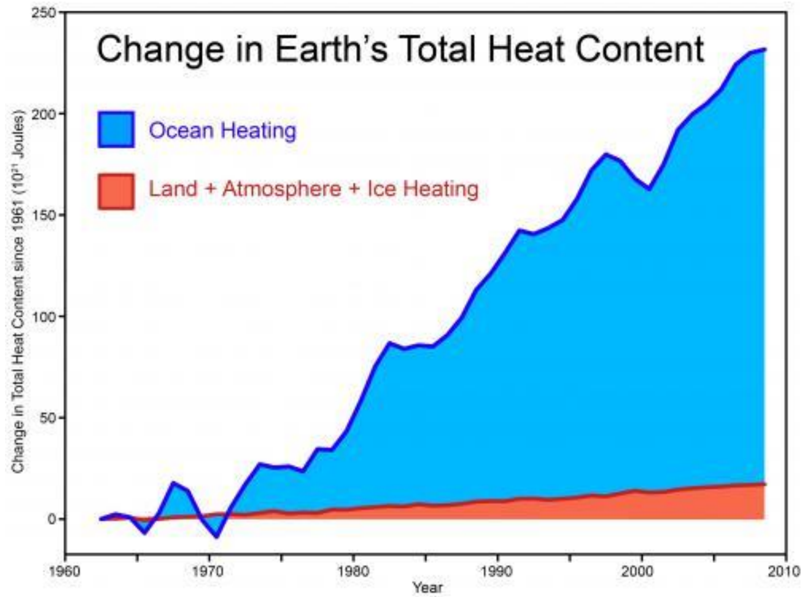


Figure 2: Graph showing the change in Earth's total heat content since 1961 (Cook, 2011)

2.1.3) Sea Level Rise

Sea level rise is a consequence of heat being absorbed into the ocean due to climate change for two reasons. First, the increase in ocean temperature is contributing to global sea level rise due to the thermal expansion of water (EPA, 2010). Second, the increase in global temperatures is also causing the polar ice caps to begin melting, which further contributes to a greater volume of water (Shah, 2012). Each decade, the relative sea level rise along the U.S. coastline has been measured at 0.4 to 4 inches (TBHA, 2013). Specifically in Boston, relative sea level rise has been about one foot in the past century. By 2050, it is predicted via current models that Boston will experience up to two feet of sea level rise, with a possible six feet increase by the year 2100 (TBHA, 2013).

2.1.4) Changes in Precipitation Patterns

The increase in global temperature caused by climate change is also leading to changes in precipitation patterns. As air becomes warmer, more water evaporates into the atmosphere, contributing to increased precipitation (EPA, 2010). Shifts in air and ocean currents change weather patterns, altering the location and amount of precipitation that falls. Some areas experience a decrease in precipitation, which leads to frequent, severe droughts (EPA, 2013). Other areas, such as the northeast region of the United States, are expected to see sharp increases in precipitation, which will be discussed in more detail in the subsequent subsection (EPA, 2010).

2.1.5) Increased Severity of Storms

The combination of sea level rise and changes in precipitation patterns is leading to the increased severity of storms. On average, severe precipitation events currently occur every twenty years. It is estimated that by the year 2100, severe precipitation events will occur every four to fifteen years (EPA, 2013). An example of a severe precipitation event is Hurricane Mitch, where flooding due to heavy rainfall killed over 11,000 people in Central America in 1998 (Cimons, 2013). The increase in the amount of storm surge contributed to this natural disaster.

Storm surge is the abnormal rise of water above estimated tide levels due to storm-related low air pressure and high winds (TBHA, 2013). An example of storm surge occurred during Hurricane Katrina, where storm surges rose twenty-five to twenty-eight feet above normal tide levels, causing major damage along coastal areas (NHC, 2008). In addition, the severity of storms is predicted to increase due to a projected 6-18% increase in rainfall during hurricanes (EPA, 2013). This combination of sea level rise, changes in precipitation, and increased storm severity poses flood threats in coastal areas.

2.2) Categorizing the Threat of Flooding

Flood damage is usually divided into two categories, direct and indirect, and then subdivided further into tangible and intangible damage. Examples of each type can be found in Table 1 and will be discussed in detail in subsequent subsections. Direct damage occurs at the time of the flooding, including damage of buildings and property and immediate health effects (Aerts, Wouter, & Botzen, 2001). Further consequences that arise after flooding are categorized as indirect damage. Examples of indirect damage include the disturbance of public services, transportation, and trade. Tangible damage can be readily assessed in financial terms, while intangible damage is more difficult to express in terms of dollars. An example of intangible damage would be long-term health effects to people.

	Tangible	**Intangible**
Direct	Damage to Buildings	Loss of Life
	Damage to Content of Buildings	Loss of Environmental Properties
	Damage to Infrastructure	Inflicted Negative Health Effects
Indirect	Disruption of Traffic	Problematic Post-Flood Recovery
	Loss of Business Production	Increased Vulnerability of Flood Survivors

Table 1: Examples of Tangible/Intangible and Direct/Indirect Damages

Tangible, intangible, direct, and indirect damages can be grouped into the following categories, which will be elaborated in succeeding subsections:

- Public health impacts from flooding and storms
- Economic impacts of flooding
- Social impacts of flooding
- Ecological effects of flooding

2.2.1) Public Health Impacts from Flooding and Storms

Health problems are associated with water damage and severe weather (Mendell, Mirer, Cheung, Douwes, 2011). These problems include respiratory issues, gastrointestinal infections, the increased geographical range for disease, and mental health issues. These issues will be elaborated in subsequent paragraphs.

First, respiratory issues are a common health consequence of flooding. Short-term exposure to mold causes minor problems such as nasal congestion, eye and skin irritation, and wheezing. Long-term exposure can cause serious problems such as fevers, shortness of breath, obstructive lung disease, lung infections, hypersensitivity pneumonitis bronchitis, and asthma (Mendell, Mirer, Cheung, Douwes, 2011). Dampness in buildings increases the chance for mold and fungi infestations, as they grow in warm, damp, and humid conditions. Severe mold infestations can develop from water damage. The EPA defines severe infestations as those over ten square feet, which need to be removed by specialists (Mendell, Mirer, Cheung, Douwes, 2011).
Common indoor molds include Cladosprium, Penicillium, Alternaria, and Aspergilus (EPA, 2012). People without a history of asthma can develop this respiratory condition after exposure

to mold. It is especially dangerous for children to be in contact with mold, as it can increase their susceptibility to asthma and respiratory allergies. These infestations pose serious health effects for people who try to remove them with bleach and water (Mendell, Mirer, Cheung, Douwes, 2011).

Second, gastrointestinal illnesses are other common health consequences of flooding. Various food-borne, water-borne, and animal-borne diseases can also be caused by flooding, coupled with water contamination resulting from failed wastewater treatment and chemical contaminants (EPA, 2012). Warm, damp areas increase the growth rate for bacteria, such as salmonella. These bacteria can contaminate food, water, and surfaces, causing various gastrointestinal diseases. Flooding and rainfall can increase the spread of water-borne diseases, such as Cryptosporidium and Giardia (EPA, 2012). Severe cases with no medical treatment can cause death.
Third, the geographical range for animals carrying diseases can increase during flooding. Ticks carrying Lyme disease and mosquitoes carrying the West Nile virus survive better in warm, damp areas (EPA, 2012).

Lastly, mental health issues can also arise as an impact of flooding. Many individuals experience stress and anxiety during flood recovery (Tapsell et al., 2002). This can affect both the person experiencing the stress and their families.

2.2.2) Economic Impacts of Flooding

There are numerous economic effects of flooding, including direct and tangible damage to property caused by storms and the hydrostatic force of flood water (Jones, 2009). These can cause short-term problems, such as the damaging of walls, windows, and foundation. In New York and New Jersey, Superstorm Sandy destroyed 900 buildings and critically damaged over 12,000 more (Newman, 2012). These damages can have a negative economic impact on the area. The structural damage caused by Superstorm Sandy left 2.76 million people without power and caused an estimated $50 billion of damage (Stone, 2012).

In addition, indirect and tangible economic effects can result from flooding. An example of this is businesses closing or experiencing loss of activity, which impacts the economy. Stores and restaurants could also experience a loss or disruption of supplies, causing another negative economic effect (IRS, 2013).

2.2.3) Social Impacts of Flooding

Flooding has huge social impacts on communities. The loss of materialistic items that are "priceless," such as family heirlooms or photographs is often more upsetting to people than items of significant financial value (Tapsell et al., 2002). Loss of assets is both tangible and intangible. This can be a direct or indirect, intangible social threat because many times in severe flooding, the lives of victims are negatively impacted. This is due to the amount of stress and hardship endured through the process of fixing or replacing the lost property and possessions.

Quality of life, an intangible impact, may also be affected by flooding when people are forced to relocate. Following Superstorm Sandy, most school systems in New York City were temporarily closed, and the subway system was not running due to flooding in the tunnels. Closing of schools and subways caused people to change their daily lives previous to the flooding, resulting in both tangible economic impacts and intangible social impacts. People had to find different routes to travel and places for their children to go while they went to work. In addition, the Park and Recreation Department closed all of the city's parks, playgrounds, and beaches. Communication between people was also limited due to power outages. This loss of social connection caused many people's normal lives to be disrupted (Newman, 2012).

2.2.4) Ecological Effects of Flooding

Many negative ecological effects take place as a result of saltwater flooding. First, a sudden dramatic increase in primary productivity can result from flooding, such as the growth of algae. This is usually the first noticeable ecological sign after flooding occurs (Sims, 2012). Second, annual flowering plants and vegetable plants will often be killed upon impact with salt water (Stiffler, 2001). Third, the presence of raw sewage in floodwater due to the combined sewage overflow system leaves unclean water pooling in public areas and impacts both ecological and human health (TBHA, 2013). Wildlife and fish health can be at risk when pollutants, solids, nutrients, and toxins in combined sewage overflow are present. Destruction to aquatic habitats can also result from the presence of combined sewage overflow (Department of Ecology, 2011).

2.3) Potential Impacts from Flooding in Boston

Global sea level rise and increased storm severity put Boston at risk for flooding and its resulting effects. Figure 3 shows the current coastline of Boston in comparison to Figure 4, which shows possible widespread flooding of the city at today's high tide plus 7.5 ft. The yellow area in Figure 4 represents sea level rise of 0-2 ft, pink represents sea level rise of 2-4 ft, and orange represents sea level rise of 4-6 ft. Today's high tide plus 7.5 ft is equivalent to the estimated 100-year flood in 2100 (TBHA, 2013).

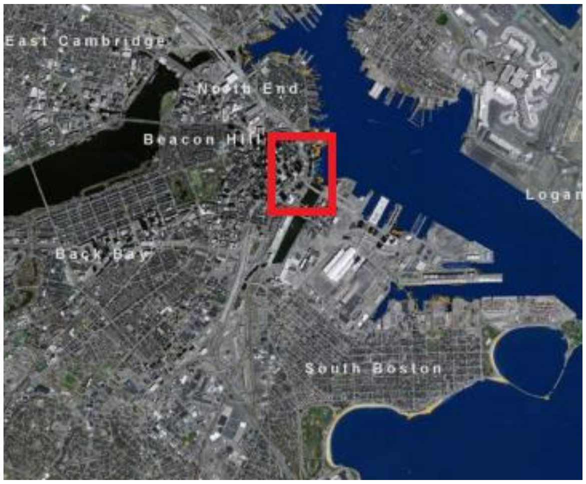


Figure 3: Current map of Boston's coastline (TBHA, 2013)

Figure 4: Flooding at today's high tide plus 7.5 ft (TBHA, 2013)

It is important to note that the flood zone map in Figure 4 is an underestimate of the actual flooding that may occur because it only examines the effect of rising sea levels. The map does not take wave activity or other environmental factors into account. By not considering these factors, a false sense of security may be held by stakeholders. Their urgency to take action against flooding may be significantly decreased.

2.3.1) Reducing Vulnerability in Boston

In response to sea level rise predictions, as seen in Figure 4, numerous agencies and groups are working to help Boston achieve lower vulnerability to flooding due to climate change. This includes the state government, the city government, the Boston Redevelopment Authority, and other public and private parties. Many organizations either have created or will create plans for implementing strategies to reduce the damage from flooding.

For example, in April, 2013 the Commonwealth of Massachusetts passed Bill S.344188th, which proposed to create a process of evaluating exposure to flood damage caused by climate change. An appointed advisory committee will create a report including the following four assessments by October, 2014 (188th General Court, 2013):

1. A set of combined sea-level rise and storm-surge scenarios for Massachusetts.
2. Estimates of risk levels of each scenario occurring by 2030, 2050 and 2100.
3. Estimates of flood water levels in coastal areas under each scenario which shall reflect appropriate local information such as local uplift and subsidence, and coastal erosion rates.
4. Estimates based on hydrological and hydraulic modeling of flood water levels in each scenario in historically coastal areas now currently protected by dams, including the Charles River Basin and the Mystic River Basin.

At the local level in Boston, Mayor Menino created the Climate Action Leadership Committee and the Community Advisory Committee in 2009 (City of Boston, 2011). He proposed that the two committees produce goals to reduce greenhouse gas emissions within the community, a strategy to allow Boston to resist climate change effects, and reasonable procedures to allow for fairly distributed benefits and financial responsibilities for the changing climate resistance. The committees agreed on the following five recommendations (City of Boston, 2011):

1. Greenhouse gas emissions should be reduced by 25% in 2020 and 80% in 2050.
2. Strategies to combat climate change need to be immediately implemented in all activities planned by the city government.
3. City government needs to be the leader of unifying the efforts of all community segments in climate action.
4. Boston needs to cultivate skills in the workforce and advanced businesses to combat climate change.
5. Everyone in the Boston community should be conscious of exercising leadership in the plan of reducing climate change effects.

A local government organization planning for climate change impacts is the Boston Redevelopment Authority (BRA). The BRA is completing several tasks to improve Boston's preparedness for flooding due to climate change. They have made plans to survey all buildings and structures vulnerable to climate change to understand the preparedness of each specific site. In addition, they are ensuring that new developments are required to include climate change preparedness in their design. They are also enforcing climate-preparedness guidelines and checklists as provided by Article 80 Development Review Guidelines (Boston Redevelopment

Authority, 2013). They are currently analyzing the at-risk area between Christopher Columbus Park and Fort Point Channel, shown in Figure 5.

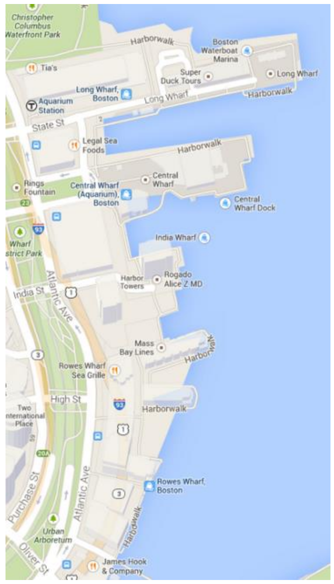
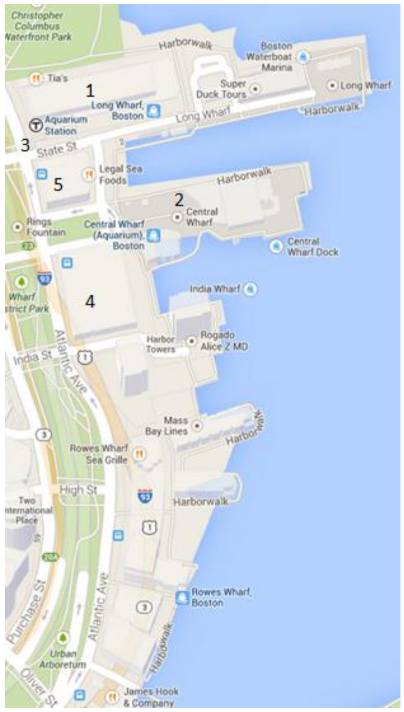


Figure 5: Map of the study area (*Google Maps)*

Private organizations, such as The Boston Harbor Association, are working to address the issue of climate change in Boston as well. In February, 2013, The Boston Harbor Association published their report, *Preparing for the Rising Tide*, in which they conducted thorough research on the risk of flooding in the area between Christopher Columbus Park and Fort Point Channel. This report provides suggestions of strategies to reduce the risk of flooding due to climate change. They assessed the following buildings which are shown in Figure 6:



Key:
1: Marriott Long Wharf Hotel
2: New England Aquarium
3: Aquarium MBTA Station
4: Harbor Garage
5: 255 State Street

Figure 6: Map showing buildings assessed in TBHA's report (*Google Maps*)

Long Wharf and Marriott Hotel: The Long Wharf was first constructed in the 17th century and was the center of the shipping industry for numerous centuries. The Big Dig project installed an expressway below the wharf, which is currently the Blue Line in the MBTA's T system. Included in the Long Wharf area is the Marriott Hotel, built in 1982. The hotel lobby is placed on the second floor of the building, while a restaurant and coffee stand are stationed on the first floor (TBHA, 2013).

New England Aquarium and Aquarium MBTA Station: The New England Aquarium complex includes the exhibit building and the IMAX Theater, and it extends into the office space on the first floor of the Harbor Garage. The basement of exhibit building is protected by two sump pumps, and the IMAX Theater does not have a basement or backup power. During extreme storm surges, the drain system overflows into the Boston sewer system, which causes flooding in the surrounding areas (TBHA, 2013).

255 State Street: Constructed in 1916, this building's purpose is mainly for offices and retail space. Currently a notable chain that is located in this building is Legal Sea Foods. Its ten-foot-high basement is comprised of service equipment, storage, and two sump pumps. All of the elevator and emergency equipment are located on the roof of the building (TBHA 2013).

Harbor Garage: This garage was built in 1969 as a component to the Harbor Tower complex. The basement of the garage has two floors, one for parking and one for service equipment. At ground level, there is office space (TBHA, 2013).

To assess these buildings and provided appropriate recommendations for strategies to reduce flood risk, TBHA conducted a vulnerability assessment on each building.

2.4) Vulnerability and Adaptation to Flooding

The vulnerability of a system to flooding is a function of its exposure to a flood event, its susceptibility to a flood event, and its ability to cope with a flood event. The ability to cope with a flood event involves resilience and resistance. Resilience and resistance are related to the features of a specific site and how they function during a flood. Flood resilience, also known as wet floodproofing, is a technique in which structural damage due to flooding is reduced; however, water is not actively prevented from entering. Flood resistance, or dry floodproofing, prevents floodwater from entering the building entirely. Finally, flood avoidance is the relocation of the building or inhabitants from any area at risk of flooding (Bloch, 2012). A system is most vulnerable if it is more susceptible to flooding and less resilient and resistant to floodwaters (TBHA, 2013).

2.4.1) Susceptibility to Flooding

One way to measure susceptibility is by the amount of potential damage that could be incurred in a flood. This depends on the critical elevation of various components such as windows, doors, sewer lines, HVAC systems, electrical outlets, and generators. These are all prone to damage from seawater, and the damage of these components could be critical, or seriously detrimental, to the function of the building. The elevation of each of these components corresponds with the height at which floodwater could cause damage. A low elevation makes a component more vulnerable. Maps such as Figures 3 and 4 show the projected heights of floodwater over time. These heights can be used to determine approximately when a building could be damaged based on the height of openings and service equipment. If a feature of a building is equal to or lower than the projected floodwater, then there is potential that it could be damaged. Therefore, it is sometimes possible for an area to flood but not cause any substantial damage because water does not reach the height of critical components. This idea has been built upon by The Boston Harbor Association.

2.4.2) Resilience to Flooding

The Boston Harbor Association has coined the phrase “Living with Water” to describe the idea of allowing an area to flood and to only take measures to minimize the resulting damage (TBHA, 2013). The belief behind this idea is that coastal flooding will undeniably be increasing, so it is necessary to begin taking preparatory measures now for flooding that is predicted in the near future. Service equipment, such as electrical boxes, HVAC systems, sewage systems, and other components of the building, can be raised within the structure to avoid damage from flooding, thus reducing susceptibility. For example, electrical sockets and wire junctions can be at higher levels within the walls to avoid water damage. Also, the sub-structure and superstructure components of the building can be designed in a way so that they can dry out quickly. Other improvements, such as food and medicine provisions and escape routes, can be accessible within the structure to improve the building's flood resilience (Bloch, 2012).

Figures 7 and 8 show an example of flood resilience on the Cheong Gye Cheon Channel in Seoul, South Korea. This channel provides a below-grade social space when flooding is not present as well as a place for water to flow into during times of flooding (TBHA, 2013).

Figure 7: The Cheong Gye Cheon Channel without flooding (TBHA, 2013)

Figure 8: The Cheong Gye Cheon Channel is closed off when it floods (TBHA, 2013)

2.4.3) Resistance and Avoidance to Flooding

In contrast to these resilience strategies, the purpose of resistance strategies is to keep floodwater out of an area. Flood-resistant designs need to consider points of the structure where water could potentially enter. Features such as windows, doors, floor voids, and cracks within the walls could all be areas vulnerable to allow floodwater into a building. Also, the quality of the materials used to construct the building is critical. If a portion of the structure fails, such as the collapse of a wall, water could enter the building through the damaged area (Bloch, 2012). In comparison to resilience strategies, resistance strategies have many disadvantages. They are usually very expensive, require constant maintenance, and have short lifespans. Resistance strategies can also cause various ecological problems (TBHA, 2013). An example of a strategy displaying these disadvantages is a levee. During Hurricane Katrina in New Orleans, the city’s levees failed due to inadequate maintenance, and this resulted in $40-50 billion worth of flood damage (NBC, 2009). Since resilience strategies usually do not have as many negative impacts, they can be favored over resistance strategies. Likewise, they are favored over flood avoidance strategies.

Flood avoidance, especially for existing buildings, is a controversial procedure that does not involve the use of resilience or resistance strategies (Tam, 2009). Abandoning property in severe flood zones and allowing flood waters to enter areas without resistance is an example of flood avoidance. It is a controversial approach that is usually not considered because it involves abandoning entire communities (Bloch, 2012). Therefore, resilience and resistance strategies are usually preferable over avoidance.

2.5) Vulnerability Assessments Conducted in Preparing for the Rising Tide

The vulnerability assessments in *Preparing for the Rising Tide* were professionally completed, in association with TBHA, by Chris Watson and Ellen Douglas from the University of Massachusetts-Boston and Paul Kirshen from the University of New Hampshire. They completed these assessments by obtaining site plans from building managers and using a GPS and an altimeter to take measurements of elevations.

The critical elevations in *Preparing for the Rising Tide* were vertical measurements of openings and service equipment that could be damaged by salt water. The measurements made as part of this report are given in terms of the North American Vertical Datum of 1988 (NAVD 88), which is a vertical measurement in relation to a single point of origin on the continent (TBHA, 2013). The report states that Boston's average high tide is 4.8 ft NAVD. Also, the report includes analyzed critical elevation points at 9.8 ft and 12.3 ft NAVD, which correspond with today's 100-year storm and the projected 100-year storm in 2100, respectively. The elevations are different because average sea levels are projected to rise about 6 ft by 2100 (TBHA, 2013). The critical elevations measured at each of the buildings are summarized in Table 2. The summary of findings from this report is explained here to show the basis of measurements that we took for our project. The first four elevations listed are less than 9.8 ft NAVD, meaning that the building could be damaged during today's 100-year storm. The main door of the Aquarium IMAX was less than 12.3 ft NAVD, meaning that the building could be damaged during the projected 100-year storm in 2100. These measurements of the elevations of buildings along with projected sea level rise determined whether these buildings were vulnerable to flooding. The report then includes specific flood resilience strategies to address these vulnerabilities.

Building	Critical Elevation	What Could be Damaged at the Critical Elevation
Marriott Long Wharf Hotel	7.5 ft NAVD	Below-ground garage
Aquarium MBTA station	7.5 ft NAVD	Above-ground entrance
255 State St	9.5 ft NAVD	Street level entrances
Harbor Garage	9.5 ft NAVD	Entrance
Aquarium IMAX	11 ft NAVD	Main door
New England Aquarium	15 ft NAVD	First floor (all electrical equipment and generators are located on the second floor)

Table 2: Summary of critical elevation results in *Preparing for the Rising Tide*

2.6) Specific Flood Resilience Strategies

Cities all over the world are implementing strategies to reduce and cope with damages caused by flooding. Government and nongovernment organizations in cities such as Amsterdam, San Francisco, Toronto, New York City, New Orleans, Tokyo, Rotterdam, and London have been analyzing property and implementing strategies to protect these cities from water damage (Carmin, 2012). Many of these strategies from countries around the world have proven successful, and others have shown promising signs. Similar strategies implemented in other cities can be implemented in Boston to protect property along the Harbor. From methods already developed and practiced, a protection system for Boston can potentially be developed.

The following flood resilience strategies are examples that have been successfully implemented in coastal cities around the world and can reduce and cope with flood damages that. The list is organized into short- and long–term strategies. The short-term strategies are strategies can be implemented for buildings that are currently at risk or will be in the near future. Long-term strategies can be implemented at locations that will be at risk in the future, as sea levels continue to rise. For example sea levels in Boston are project to rise up to 6 ft by the year 2100. The strategies are presented in more detail in Appendix A.

Short-Term Strategies

- **Emergency preparedness strategies**: This consists of supplies and actions that building managers plan for their buildings during severe weather and flooding.
- **Flood sealants and shields**: Flood sealants are waterproof coatings and injections that can seal openings in buildings. Flood shields are barriers that can be placed around openings to stop water from entering windows and doors.
- **Backflow valves for sewage management**: Valves can be installed to prevent the backup of sewage during high water levels.
- **Improved building materials**: These building materials are water resistant to protect different aspects of buildings from significant water damage.
- **French drains**: These fairly inexpensive drains divert water from buildings to a different location.

- **Increasing vegetation**: Vegetation can reduce the effects of storm surge and provide minor absorbance effects of water.

Long-Term Strategies

- **Breakaway walls:** These walls are not part of the structural supports of buildings, which collapse when put under pressure from flooding and storms.
- **Raised roads**: Raising roads can protect important travel routes during flooding and help divert water away from buildings.
- **Floodable developments**: The use of garages or cisterns diverts excess water during storm events.
- **Retention ponds**: Public spaces can be converted into water collection spaces during storm events.
- **Rain gardens**: Areas of vegetation can infiltrate storm water back into the soil to reduce flooding.
- **Drainage systems and permeable pavement**: Expanding drainage systems can aid cities in handling large amounts of floodwater. Permeable pavement is specially designed pavement that allows water to flow through it, so that the water is filtered and can safely enter city drains.
- **Elevation strategies**: All buildings can raise their critical service equipment to higher levels than the bottom floor. Buildings may also consider moving important rooms and inventory above the first floor. A more drastic, but potentially very beneficial idea is to raise buildings above flood levels. Some buildings can also temporarily be raised through the use of flotation devices.

- **Living shorelines**: Wetlands and biological habitats have beneficial ecological effects and can protect shorelines from erosion and storm surge.

2.7) Summary

Boston is at an increasing risk for flooding caused by climate change, and it is possible for strategies used by other coastal cities to be adjusted to fit the specific needs of Boston. In *Preparing for the Rising Tide*, TBHA assessed some of the buildings along the Boston waterfront and proposed specific resilience strategies to reduce the risk of flood damage at those sites. These buildings included: the Marriot Long Wharf Hotel, the Aquarium MBTA Station, 255 State Street, the Harbor Garage, and the New England Aquarium. However, there are other important buildings and areas that are also vulnerable to flooding that were not studied in this report. These buildings included James Hook Lobster Company, the Coast Guard Building, the Rowes Wharf Complex, the Harbor Towers, and Christopher Columbus Park. To fully inform the BRA and other planning committees, more information and additional vulnerability assessments on these sites are necessary. Our methodology for this assessment will be discussed in detail in the following chapter.

3) Methodology

The Boston Redevelopment Authority is in the process of revising the Municipal Harbor Plan between Fort Point Channel and the Christopher Columbus Park in Downtown Boston. The goal of our project was to provide the BRA with recommendations for resilience strategies to reduce damage from rising sea levels and increased storm severity. To achieve this goal, we completed the following objectives:

1. Assess the vulnerability of buildings in the study area of Downtown Boston to sea level rise and storm surge. We focused on the buildings in the Downtown Boston area that were not previously assessed in *Preparing for the Rising Tide.*
2. Identify strategies to increase resiliency that have been proposed or implemented in other cities and assess their strengths, weaknesses, and feasibilities.
3. Gather expert feedback on strategies that can be applied to the study area.

The outcome of these objectives was a set of recommendations presented to the BRA. In the following sections, we describe the methods used to achieve our research objectives.

3.1) Objective 1: Assess the vulnerability of buildings in the study area of Downtown Boston to sea level rise and storm surge.

There are ten buildings in the study area of Downtown Boston; five were assessed by TBHA and five by our project team. We assessed James Hook Lobster Company, the Coast Guard Building, the Rowes Wharf Complex, the Harbor Towers, and the Christopher Columbus Park.

Before we could propose strategies to increase resilience of sites in the study area, we had to determine the vulnerability, specifically the critical elevation. A critical elevation is the height at which components of buildings become vulnerable to the threats of rising sea levels and storm surge. For example, certain components of buildings, such as stairs leading to a building, can flood without causing damage. However, if the first floor of a building begins to flood, this could cause serious damage. In this section, we discuss how we determined which buildings to assess, the methods we used to determine vulnerability, and how we conducted our assessments.

3.1.1) Selecting Buildings and Areas for Vulnerability Assessments

Preparing for the Rising Tide included vulnerability assessments on the following buildings:

1. The Marriott Long Wharf Hotel
2. The New England Aquarium
3. The Aquarium MBTA Station
4. The Harbor Garage
5. 255 State Street

For our project, we completed similar vulnerability assessments for the remaining buildings in this study area of Downtown Boston, using the same approach as the TBHA report, as described in Background chapter 2.5. These buildings included the James Hook Lobster Company, the Coast Guard Building, the Rowes Wharf Complex, the Harbor Towers, and the Christopher Columbus Park, shown in Figure 9. Using both the vulnerability assessments completed by TBHA and by our project, we were able to understand the vulnerability of the entire Downtown

Boston area. This allowed us to provide recommendations to the Boston Redevelopment Authority for resilience strategies that could be applied in Downtown Boston.

Key:
1: James Hook Lobster
2: Coast Guard Building
3: Rowes Wharf Complex
4: Harbor Towers
5: Christopher Columbus Park

Figure 9: Map showing sites assessed in our report (*Google Maps*)

To provide vulnerability assessments on buildings and areas throughout Downtown Boston, we had to become familiar with the sites. We researched the varying histories, components, and purposes of each structure, which gave us insight into which strategies could potentially be used in order to increase resilience in the area. We gathered the following information on the buildings not assessed in *Preparing for the Rising Tide*.

James Hook Lobster Company: This waterfront lobster company was founded by James Hook and his three sons in 1925 (James Hook Lobster Company, 2013). In 2008, James Hook Lobster Company was severely damaged by a fire. The aftermath of this tragedy included about $5 million in damages and over 600,000 pounds of lobster lost (Sauer, 2008). Today, they ship over 500,000 pounds of lobster every day from a temporary unit at the same location near Fort Point Channel (James Hook Lobster Company, 2013).

Captain John Foster Williams Coast Guard Building: This homeland security building was built in 1918 and was renovated in 1980. Its estimated height is 114 ft and contains 8 floors above the ground (Emporis, 2013).

Rowes Wharf: This historic wharf was originally built in 1764 for mainly industrial water traffic into the Harbor. However, by the 20^{th} century, the wharf became a rundown and undesirable area, with the amount of commercial traffic drastically decreased. However, the "New Rowes Wharf" brought life back, as the 5.38 acre site became the "Gateway to Boston." The new wharf, completed in 1987, is 182 ft high with 16 stories. It also contains the four-star Boston Harbor Hotel, which contains 230 rooms, 100 luxury condominiums, and essential marine facilities (A View on Cities, 2010).

The Harbor Towers: Along the Harborwalk are two 400 foot residential towers with 624 units known as the Harbor Towers. These 40 story residential condominiums were completed in 1971 to begin a project by the Boston Redevelopment Authority to bring more life to the Boston Harbor waterfront. The towers were built with a concrete, brutalist architecture theme, which was controversial at the time, since this did not match the typical architecture of other Boston buildings (TBHA & BRA, 2013).

Christopher Columbus Park: This was Boston’s first waterfront park, opened in 1976. In 1987, the granite fountain and iron fencing was added, and more renovations were made in 2003 (TBHA & BRA, 2013). The park is an open public space used for recreation for the Downtown Boston community. This site is included in our report as a potential site for implementing neighborhood resilience strategies.

3.1.2) Methods for Determining Vulnerability of the Selected Buildings and the Park

For our project, we used similar methods to determine vulnerability as *Preparing for the Rising Tide*. We first used surveying equipment to measure the critical elevations of buildings in our study area. We measured critical components, such as the height of the main doors, electrical equipment, and openings to garages. To survey these components, we used known sea level reference points to determine when areas along the Downtown Boston waterfront will begin to flood. Table 3 summarizes key ocean level elevations during today’s high tide, today’s annual storm, and today’s 100-year storm.

Measurement Reference	Description of Reference Term	Water Elevation
Today’s High Tide	Average high tide in a given year	4.8 ft NAVD
Today’s Annual Storm	Average storm in a given year	7.5 ft NAVD
Today’s 100-year Storm	Storm with 1% chance of occurring in a given year	9.8 ft NAVD

Table 3: Summary of key reference water elevations

Sea levels in Boston are projected to rise one to two feet by 2050, and three to six feet by 2100. We defined each measurement we took as high vulnerability, moderate vulnerability, or low vulnerability to flooding, as seen in Table 4. Buildings that are affected by today's high tide, annual storm, or 100-year storm are considered at a high vulnerability to flooding and immediate action must be taken. Buildings that could be affected by the 100-year storm in 2050 or 2100, but not by today's high tide, annual storm, or 100-year storm, are at a moderate vulnerability to flooding and action must be taken in the near future. Buildings that are not affected by any of these ocean levels are at a low vulnerability because they are not likely to be affected in the foreseeable future.

Water Elevation that Begins to Affect Building (ft NAVD)	**Vulnerability to Flooding**	**Measurement Reference**
Below 10	High	Today's High Tide, Today's Annual Storm, or Today's 100-Year Storm
10-14	Moderate	Predicted 100-Year Storms in 2050 or 2100
Above 14	Low	No Expected Water Damage

Table 4: Summary of vulnerability definitions

After determining how likely buildings are to experience flooding in the future, we determined how severe consequences could be for this study area if flooding did occur. This added dimension of determining the consequences of flooding was not completed in *Preparing for the Rising Tide*. Risk is a function of how likely buildings are to flood and how severe the consequences could be. For example, a building might be at a high likelihood to flooding, but the damage caused by flooding might be minimal, so it would be at low risk. To conduct risk assessments, we identified previous reports and spoke with building managers about critical equipment. Based on this information, we made preliminary determinations of the types of consequences that could occur in our study area. We judged the consequences based on how crucial a component was to the function of a building.

Table 5 shows the chart developed by the ICF International to understand risk assessment for climate change hazards. This shows the link between the likelihood of an event occurring and the degree of consequence, ranging from catastrophic to insignificant. The red areas are defined as a high risk to flooding, the orange areas are a moderate risk to flooding, the yellow areas are a low risk to flooding, and the white areas are insignificant to flooding. For example, in Table 5, cell 2C is considered at high risk; there are major consequences to flooding and a medium likelihood of occurring. The report defines a catastrophic consequence as a huge financial loss with permanent damage to infrastructure, the environment, and human health. An insignificant consequence causes no infrastructural damage, minimal financial losses, no adverse human health effects, and minimal impacts to the environment (ICF International, 2009).

Likelihood	**Consequence**				
	1.Catastrophic	**2.Major**	**3.Moderate**	**4.Minor**	5.Insignificant
A. Very likely	1A	2A	3A	4A	5A
B. Likely	1B	2B	3B	4B	5B
C. Medium	1C	2C	3C	4C	5C
D. Unlikely	1D	2D	3D	4D	5D
E. Very unlikely	1E	2E	3E	4E	5E

Table 5: Qualitative evaluation of likelihood and consequence of hazardous events (ICF International, 2009)

3.1.3) Conducting our own Vulnerability Assessments

Our vulnerability assessments for the five sites in our study area were completed in the following steps.

First, we requested meetings with building owners and requested access to site plans. We were able to acquire the plans to the Rowes Wharf Complex and the Harbor Towers. From the Rowes Wharf Complex, we spoke with the senior property manager, Joe Gibbons, and from the Harbor Towers we spoke with the facilities manager, Fran Higgins, and the building manager, Hugh Schaffer. During these meetings we obtained site plans and were shown the locations of all critical equipment. Some of the specific questions we asked to provide a general structure to the interview included:

- Are you informed about the dangers of sea level rise?
- Has this building experienced any flooding in the past? If so, what was the damage?
- Have there been any past renovations done to this site? Are there any renovations planned for this site in the future?
- Are site plans available in order to aid in the determination of elevations of critical equipment?
- Are there emergency preparedness plans in place at the site?

We each recorded the information discussed during these interviews through personal notes. For security reasons, we were unable to obtain the site plans or information about the inside of the Coast Guard Building. This was a limiting factor to our analysis because we were only able to measure the elevations of visible openings and service equipment from the outside. We were also unable to receive site plans for James Hook Lobster Company and the Christopher Columbus

Park. Although a complete vulnerability assessment could not be performed for these sites, we gathered enough information to provide suggestions for flood-resilience strategies.

Second, using surveying equipment provided by Worcester Polytechnic Institute, we measured the critical elevations of each building. This equipment had the capability of measuring to the nearest one-thousandth of a foot. We measured critical elevations on the outside of all of the buildings and used site plans to determine the elevations of critical equipment inside of the buildings, when possible. This involved measuring the elevation of all openings to the building, including doors, windows, entrances to garages, and service equipment, including electrical equipment and HVAC systems. Our surveying route is illustrated in Figure 10 and all of our measured components for each site are listed in Table 6.

Figure 10: Map showing general pathway of surveying (*Google Maps*)

Site	Measured Components
James Hook Lobster Company	• Base of the building • Main Door • Windows • Raised HVAC equipment
Coast Guard Building	• Outdoor HVAC and electrical equipment • Top of seawall • First floor
Rowes Wharf Complex	• Seawall • Ferry terminal door • First floor of condominiums • Outdoor electrical outlets • First floor doors • Main doors • Vent in front of garage • Top of dock caps
Harbor Towers	• Height of shorter seawall • Opening in air vent • Outside grate leading to service • Outdoor electrical outlets • Main entrance to east tower • Main entrance to west tower
Christopher Columbus Park	• Seawall • Electrical boxes on dock • Christopher Columbus statue • Trellis walkway

Table 6: Measured components of each building

The members of our group did not have much experience with using surveying equipment, but we followed a few procedures outlined in *Preparing for the Rising Tide* to ensure our accuracy. We performed a couple of practice loops starting at a known elevation point and ensured that when we returned to this point, the elevation was the same. Once we felt confident in our ability to measure these points with minimal error, we measured the buildings which had not yet been assessed.

We began our surveying loops at the city benchmark outside the Coast Guard Building. This benchmark had an established elevation of 13.47 ft NAVD. From this benchmark, we measured the windows, main door, and raised HVAC equipment outside of James Hook Lobster Company. First, we established our backsights and foresights. After leveling the tripod station, as shown in Figure 11, we placed the measuring rod on the benchmark in order to measure the plate as a backsight.

Figure 11: Picture of our team using surveying equipment

Once this measurement was taken, the measuring rod was then placed on a window on James Hook Lobster Company. This foresight measurement was taken and recorded. The tripod was then moved and re-leveled. The window's elevation was re-measured as a backsight, and then the elevation of the main door of the building was measured as the foresight. Once this was recorded, the tripod station was moved and re-leveled again, the main door became the backsight, and the HVAC equipment became the foresight. We continued in this manner around the entire loop.

Once these data points at James Hook Lobster Company were recorded, we calculated the elevations of the window, the main door, and the HVAC equipment, based off the known elevation of the starting benchmark. We then ended our loop on the benchmark and recalculated its elevation to determine our error of closure and ensure our accuracy. The error of closure needed to be less than 0.1 ft, because this was the criteria used in *Preparing for the Rising Tide*. Ideally, this second measurement of the benchmark should have been as close to 13.47 ft as possible. After ensuring our accuracy, we used a measured point as a new benchmark for the next surveying loop. We used this methodology for all subsequent surveying loops.

3.2) Objective 2: Identify strategies that have been proposed or implemented in other cities to increase resiliency and assess their strengths, weaknesses, and feasibilities.

Our team intended to learn about strategies being used across the globe that could be applied to the area between Fort Point Channel and the Christopher Columbus Park in Boston. In addition, we wanted to understand the strengths, weaknesses, and feasibilities of each strategy and assess them based on this information. Identifying these strategies was the first step in making recommendations to the BRA. To identify these resilience strategies we: 1) identified relevant sources, 2) compiled a list of potential strategies, and 3) assessed the feasibility of these strategies to the buildings and areas studied.

To acquire knowledge of these resilience strategies, we reviewed a variety of literature on the topic. We read and evaluated the following reports:

- Julie Wormser's *Living with Water* provided case studies of successful strategies used in coastal cities around the world (J. Wormser, personal communication, September 4, 2013).
- The Green Ribbon Commission's *Building Resilience in Boston* provided recommendations that building owners in Boston should apply to their buildings to reduce damage from flooding (Green Ribbon Commission, 2013).
- The City of Boston's *Municipal Harbor Plan* gave recommendations for the types of strategies that should be applied in the Downtown Boston waterfront (BRA, 2013).
- As has been stated, The Boston Harbor Association's *Preparing for the Rising Tide* recommended resilience strategies for buildings in Downtown Boston (TBHA, 2013).
- Case studies of resilience strategies from around the world, compiled by Crystal Aiken from TBHA, provided preliminary ideas about several more strategies for flood resilience that have been implemented in urban coastal areas (C. Aiken, personal communication, September 12, 2013).

We chose these reports because they contained information on resilience strategies proposed by experts and ideas of successful, creative solutions that have been implemented by other coastal cities.

After studying the literature, we compiled a list of resilience strategies and began to analyze their strengths, weaknesses, and feasibilities of implementing them in Boston. Based on our research, we categorized the strategies by certain qualities including the following:

- **Site-specific versus neighborhood strategies:** Some strategies can be applied directly to specific building sites and can be implemented by building managers and owners. These strategies can be applied in the short term to reduce the damage of flooding. Site-specific strategies are limited in their ability to reduce damage once floodwaters rise to a certain point, and neighborhood strategies then become more applicable. Neighborhood strategies can provide large-scale solutions for the entire area. However, they can be very expensive and can require coordination between city officials and building owners to be implemented.
- **Short-term versus long-term strategies:** Short-term strategies, such as installing flood shields, are generally cheaper than long-term strategies. However, long-term strategies, such as raising a seawall, may provide more reliable protection. These long-term strategies can be implemented later when a building is renovated. Either type of strategy can be useful depending on the vulnerability of a building.

We created adaptation charts using the same template as *Preparing for the Rising Tide* to summarize the strategies we identified for implementation at the five sites. These charts, which are found in Appendix B, show the degree of flooding and recommendations for each building. The templates included a timeline of projected sea level rise between 2010 and 2100 for average high tide, the annual storm, and the 100-year storm. We categorized the flood potential for each building over time and recommended resilience strategies for each level of flooding. We also provided cost estimates for these strategies based on similar projects.

To assess the feasibilities of these suggested strategies, we researched the implications of each strategy to the Downtown Boston area. Using the previously stated reports, we determined the costs, health and environmental impacts, and social implications of similar projects. This research was preliminary and the implications of these strategies will need to be further assessed before being implemented in Boston. With all of this information, we developed recommendations for resilience strategies, and we presented them to an expert review panel.

3.3) Objective 3: Gather expert feedback on strategies that can be applied to the study area.

After identifying resilience strategies from cities around the world and assessing their feasibility, we gathered expert feedback on our proposed strategies before presenting them to the BRA. First, we organized an expert review panel and proposed our resilience strategies in a two-hour discussion held at The Boston Harbor Association's office. Second, we used all of this feedback to conclude our findings and finalize our recommendations from this project in memo form, which was given to the BRA to inform them in their planning efforts for the Municipal Harbor Plan. This section outlines our methodology for how we gathered expert feedback and finalized our proposed strategies.

3.3.1) Holding a Review Panel of Experts

To better understand the application of resilience strategies to this area of Downtown Boston and to identify the most appropriate strategies, we presented our findings to a review panel of experts. This panel was comprised of:

- Scott Bishop, Stoss Landscape Urbanism
- Chris Busch, Municipal Harbor Planning Committee at the Boston Redevelopment Authority
- Andy Lipsky, SeaPlan
- Vivien Li, President of TBHA
- Chris Watson, University of Massachusetts-Boston
- Julie Wormser, Executive Director of TBHA

At this meeting, we presented a PowerPoint presentation that showed the data we collected and images of our proposed strategies. We also created packets that were distributed to each attendee, which included an agenda, our collected data, and our charts containing proposed resilience strategies. This packet is located in Appendix C. We held this meeting at lunch-time on October 1, 2013, and the entire presentation and discussion lasted two hours.

This review panel was organized around our handout and presentation. As we went through our findings and proposed recommendations, the experts discussed their opinions and provided ideas for further research. We also asked the following questions regarding our suggestions for specific buildings.

- Which of these strategies could be most difficult to apply to Downtown Boston and these specific buildings?
- What might be some problems of applying these strategies that have not already been researched?

- Are there any restrictions that could prevent these strategies from being applied to Boston?
- Which of these strategies would building owners and managers support?
- Would building owners financially support these improvements?
- Would city officials support the strategies that could alter the appearance of city sites, such as the Christopher Columbus Park?
- Do you have any further feedback on our proposed strategies?
- Are there any other strategies that we might not have researched?

Holding this review panel helped us identify which suggested strategies needed more revision before being presented to the BRA.

3.3.2) Finalizing Recommendations for the Boston Redevelopment Authority

After making the suggested recommendations obtained from the expert panel, the proposed strategies were finalized in a memo format and given to the BRA. This memo is located in Appendix B. The memo provided a short, concise summary of our findings from our vulnerability assessments of buildings in this area of Downtown Boston. It also included the charts with our proposed strategies. This memo was presented to the BRA to inform them in their efforts to revise the Municipal Harbor Plan.

4) Results & Analysis

As part of our assessment, we determined the vulnerability to flooding for the buildings in our study area and the severity of consequences that could result. We gained knowledge of the risk for each building from site visits and meeting with building managers. In this chapter we present our findings about the buildings in our study area and the resilience strategies that could be applied. For the five sites that we studied, we include findings about the 1) vulnerable features, 2) vulnerability to flooding in the short and long term, and 3) the consequences of potential flooding. Following these are our findings of the resilience strategies we identified, their implications, and their barriers to implementation. Finally, we discuss the general understanding that building stakeholders have regarding climate change and resilience strategies.

4.1) Vulnerabilities and Consequences to Flooding of James Hook Lobster Company

Finding #1: The James Hook Lobster Company is at low to moderate vulnerability to flooding. Flooding could have moderate consequences. Overall, it is at moderate risk due to flooding.

4.1.1) Vulnerable Features of James Hook Lobster Company

The original James Hook Lobster Company building burned down in 2008 and was replaced by the temporary unit which is currently in operation. We measured the elevations of the base of the building, windows, main door, and raised HVAC equipment at the back side of the building. Figure 11 shows the pathway of our surveying loop with information about the measurements taken and the error of closure. Our surveying route for James Hook Lobster Company began at the city benchmark outside of the Coast Guard Building, with a known elevation of 13.47 ft NAVD. Our error of closure for this loop was 0.071 ft.

★ Starting, established city benchmark; 13.47 ft NAVD

James Hook Lobster Company
1: Window; 19.016 ft NAVD
2: Main Door: 16.403 ft NAVD
3: Raised HVAC Equipment; 19.661 ft NAVD

★→1→2→3→★

Error of closure: 0.071 ft

: Previous building for James Hook Lobster Company which burned down; not updated on Google Maps

Figure 11: Surveying route for James Hook Lobster Company, with key showing measurements taken and the error of closure (*Google Maps*)

Figure 12: Pictures of the vulnerable features of James Hook Lobster Company (left: main door, middle: windows, right: raised HVAC equipment)

4.1.2) Vulnerability to Flooding

Projected sea levels during today's annual storm and today's 100-year storm are 7.5 ft NAVD and 9.8 ft NAVD, respectively (TBHA, 2013). The surveyed elevations suggest that this building will not be affected by today's annual storm or today's 100-year storm because the door, the windows, and the raised HVAC equipment all have critical elevations above 16 ft NAVD. However, the base of the building is at 12.3 ft NAVD, so it could begin to be affected by rising sea levels by 2050, when sea levels are projected to rise by one to two feet (TBHA, 2013).

The vulnerability to flooding for the measured features of James Hook Lobster Company are summarized in Table 7 and shown in Figure 12. The measured features are the bottom of the building, the door that corresponds with the first floor, the window, and the raised HVAC equipment on the side of the building. These features were chosen because they were the exposed openings and critical equipment on the outside of the building. Most features of the building are at a low vulnerability to flooding, while the base of the building is at moderate vulnerability. Even though this building may begin to be affected by flooding in 2050, any further assessment of its flood vulnerability is unnecessary because this temporary building will no longer be in its current location.

Location	Elevation	Vulnerability to flooding
Bottom of building	12.346 ft NAVD	Moderate
Door/ first floor	16.403 ft NAVD	Low
Window	19.016 ft NAVD	Low
Raised HVAC equipment	19.661 ft NAVD	Low

Table 7: Vulnerability to flooding for James Hook Lobster Company

4.1.3) Severity of Consequences from Potential Flooding

Due to the elevation of James Hook Lobster Company, the building is well-protected against rising sea levels and storm surge. However, the building is only temporary and could likely be damaged during severe weather due to its poor anchoring to the ground. This damage to the building would be an example of a direct and tangible consequence. Damage to the foundation of the building, or any of the critical equipment, could cause moderate consequences to the building. Table 8 shows the risk assessment chart for James Hook Lobster Company. Overall, James Hook Lobster Company is at a moderate risk to flooding because it is unlikely to flood, but there could be moderate consequences if flooding occurred.

Likelihood	Consequence				
	1.Catastrophic	2.Major	3.Moderate	4.Minor	5.Insignificant
A. Very likely	1A	2A	3A	4A	5A
B. Likely	1B	2B	3B	4B	5B
C. Medium	1C	2C	3C	4C	5C
D. Unlikely	1D	2D	3D	4D	5D
E. Very unlikely	1E	2E	3E	4E	5E

Table 8: Risk assessment for James Hook Lobster Company

4.2) Vulnerabilities and Consequences to Flooding of The Coast Guard Building

Finding #2: The Coast Guard Building is at low to moderate vulnerability to flooding. Flooding could have major consequences. Overall, it is at high risk due to flooding.

4.2.1) Vulnerable Features of the Coast Guard Building

Our surveying route for the Coast Guard Building continued the route from James Hook Lobster Company. Figure 13 shows the pathway for our surveying loop. Although we were unable to take measurements from inside of the Coast Guard Building due to its security as a federal building, we were able to take measurements of the surrounding area. At the Coast Guard Building, we measured the first floor of the building, the top of the seawall outside of the building, and the outdoor HVAC and electrical equipment. Our error of closure for this loop was 0.036 ft.

David Drevinsky, a building inspection engineer working for the Coast Guard Building, provided us with pictures of water damage that is occurring inside of the the building, seen in Figure 14. Water damage has caused the corrosion of beams, leading the building managers to undertake beam retrofits and drilling activity for beam support. Figure 15 shows pictures taken of the identified vulnerabilities of the building. The pictures include the seawall, the HVAC system, and the first floor of the building. Each of these features is critical to the function of the building.

Coast Guard Building
1: Top of stairs, corresponding to first floor of Coastguard Building; 15.063 ft NAVD
2: Top of Harbor Seawall; 10.830 ft NAVD
3: HVAC and Electrical Systems; 10.812 ft NAVD
4: End of Dock; 8.658 ft NAVD

1→2→3→4→1

Error of closure: 0.036 ft

Figure 13: Surveying route for the Coast Guard Building, with key showing measurements and error of closure (*Google Maps*)

Figure 14: Pictures of strucutral damage from inside the Coast Guard Building (left: corroded header beam, middle: spandrel beam retrofit, right: drilling activity for beam support)

Figure 15: Pictures taken of the vulnerable features of the Coast Guard Building (left: seawall outside of building, middle: outdoor HVAC and electrical equipment, right: height of first floor)

4.2.2) Vulnerability to Flooding

The vulnerability of the building to flooding is low due to the height of the first floor. However, the height of the seawall outside of the building and the outdoor HVAC and electrical equipment are at a moderate vulnerability to flooding because they are both about 10.8 ft NAVD. The seawall may not protect the critical equipment outside from rising sea levels by 2050, when sea levels could be as high as 12.8 ft NAVD. The building is relatively safe from flooding caused by sea levels today, but if sea levels rise as projected, the building could be affected by flooding in the near future. Table 9 summarizes the vulnerable features of the Coast Guard Building.

Location	Elevation	Vulnerability to flooding
Outdoor HVAC and electrical equipment	10.812 ft NAVD	Moderate
Top of harbor seawall	10.830 ft NAVD	Moderate
First Floor	15.063 ft NAVD	Low

Table 9: Vulnerability to flooding for the Coast Guard Building

4.2.3) Severity of Consequences from Potential Flooding

The Coast Guard Building is at a low to moderate vulnerability to flooding. However, the critical equipment outside could be affected by sea levels by 2050, which could cause major consequences for the entire building. If severe weather or sea levels damaged this critical equipment, important services in the building could be shut down. This would be an example of an indirect and tangible consequence. This is an important building due to its role in national defense and protection of the Boston Harbor. Therefore, this building is at a high risk to flooding because the vulnerability to flooding is moderate and the consequences could be major. Table 10 summarizes the risk assessment for the Coast Guard Building.

Likelihood	Consequence				
	1.Catastrophic	**2.Major**	**3.Moderate**	**4.Minor**	5.Insignificant
A. Very likely	1A	2A	3A	4A	5A
B. Likely	1B	2B	3B	4B	5B
C. Medium	1C	2C	3C	4C	5C
D. Unlikely	1D	2D	3D	4D	5D
E. Very unlikely	1E	2E	3E	4E	5E

Table 10: Risk assessment for the Coast Guard Building

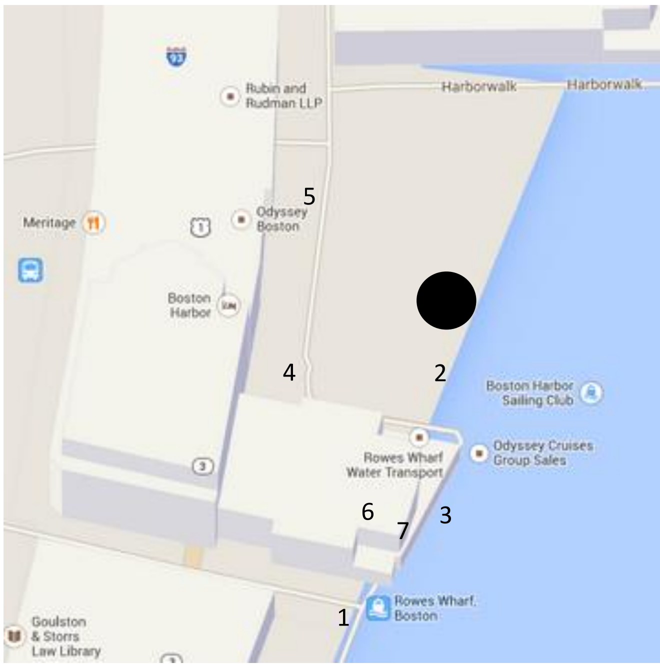
4.3) Vulnerabilities and Consequences to Flooding of the Rowes Wharf Complex

Finding #3: The Rowes Wharf Complex is at low to high vulnerability to flooding. Flooding could have major consequences. Overall, it is at high risk due to flooding.

4.3.1) Vulnerable Features of the Rowes Wharf Complex

Our surveying route for the Rowes Wharf Complex was comprised of two loops, due to the size of the area. Figure 16 shows the pathway of our first surveying loop, where we measured the height of the dock caps, the outdoor electrical outlets, the main door to the ferry terminal, and the seawall outside of the ferry terminal. Figure 17 shows the pathway of our second loop, where we measured the main entrance to Rowes Wharf, the vent in front of the garage that leads to the generator, the first floor of the condominium areas, and the seawalls. Our errors of closure for these loops were 0.014 ft and 0.019 ft, respectively.

Figure 18 shows pictures taken of the identified vulnerabilities of the complex. These pictures include the seawall, the main entrance, the dock caps, and the vent in front of the garage. All of these feaures are critical to the function of the building.



Rowes Wharf and Ferry Terminal
1: End of Dock; 8.658 ft NAVD
2: Gazebo; 9.869 ft NAVD
3: Top of Dock Cap; 15.486 ft NAVD
4: Outdoor Electrical Outlets; 13.085 ft NAVD
5: Top of Steps (Upper level of outside); 12.951 ft NAVD
6: Ferry Terminal Door; 9.781 ft NAVD
7: Seawall Outside of Ferry Terminal; 9.752 ft NAVD

1→2→3→4→5→6→7→1

Error of closure: 0.014 ft

● Gazebo not shown on Google Maps

Figure 16: Surveying route for the Rowes Wharf and Ferry Terminal, with key showing measurements and error of closure (*Google Maps*)

Rowes Wharf
1: Top of Steps (Upper level of outside); 12.951 ft NAVD
2: 50 Rowes Wharf main door in archway; 13.153 ft NAVD
3: City manhole cover on sidewalk; 12.841 ft NAVD
4: Vent in front of garage leading to generator; 13.183 ft NAVD
5: Outdoor electrical outlets; 13.427 ft NAVD
6: Top of steps leading to condos; 13.025 ft NAVD
7: Height of seawall (north); 9.652 ft NAVD
8: Height of seawall (south); 9.840 ft NAVD
9: First floor door; 13.131 ft NAVD

1→2→3→4→5→6→7→8→9→1

Error of closure: 0.019 ft

Figure 17: Surveying route for the remainder of Rowes Wharf, with key showing measurements and error of closure (*Google Maps*)

Figure 18: Pictures taken of the vulnerable features of the Rowes Wharf Complex (top left: height of seawall, top right: main entrance, bottom left: height of dock caps, bottom right: vent in front of garage)

4.3.2) Vulnerability to flooding

The building manager of the Rowes Wharf Complex, Joe Gibbons, stated in our interview that there has not been any major flooding of the complex during its short history. He also explained renovations that are planned for the building and showed us the locations of critical equipment. Even though the complex has not been affected by flooding, the locations of the critical equipment make them vulnerable:

- The emergency generator for the complex and a 3000 gallon diesal tank to power generators are located in garage floor 5, 34 ft underground.
- The main generator is located in garage floor 4, 15 ft underground.

- The main electrical swtich gear is located in garage floor 1, 3 ft underground.
- The vent outside of the garage brings air directly down to the main generator.

Most of the building is at a moderate vulnerability to flooding, with areas around the ferry terminal at high vulnerability. We also learned that the docks were recently replaced eight years ago. Our measurements showed that these docks are at low vulnerability due to the height of the caps. The building manager also said that the bricks along the plaza areas of the complex will be replaced soon due to water damage.

Although the consequences of flooding at the Rowes Wharf Complex could be moderate, the complex has a low likelihood of flooding at today's sea levels. Low-lying areas near the ferry terminal are vulnerable to flooding today. Sea levels are projected to rise to 12.8 ft NAVD during the 100-year storm in 2050, and this will not likely affect the complex. However, sea levels could rise as high as 15 ft NAVD during the 100-year storm in 2100, which could affect the entire complex. Table 11 summarizes the vulnerability of the Rowes Wharf Complex to flooding.

Location	Elevation	Vulnerability to flooding
Height of seawall	9.752 ft NAVD	High
Ferry terminal Door	9.781 ft NAVD	High
Top of steps leading to condominiums	13.025 ft NAVD	Moderate
Outdoor electrical outlets by docks	13.085 ft NAVD	Moderate
First floor doors	13.131 ft NAVD	Moderate
50 Rowes Wharf main door	13.153 ft NAVD	Moderate
Vent in front of garage (leading to generator)	13.183 ft NAVD	Moderate
Outdoor electrical outlets on street	13.427 ft NAVD	Moderate
Top of dock caps	15.486 ft NAVD	Low

Table 11: Vulnerability to flooding for the Rowes Wharf Complex

4.3.3) Severity of Consequences from Potential Flooding

The Rowes Wharf Complex is mainly at a moderate vulnerability to flooding. However, the locations of the critical equipment increase the potential damage that could be caused. The generators, diesel tank, and electrical switch gears could be at risk of damage due to their underground locations. This critical equipment services the entire complex, including the condominiums and the Boston Harbor Hotel. Damage to this critical equipment could negatively impact the residents of the building. Another serious consequence of potential flooding can occur if sea levels reach the height of the dock caps. The caps are currently at a low vulnerability, but if water reaches this height they can detatch from the dock along with all of the boats. Overall, the Rowes Wharf Complex is likely to be flooded in the future due to its moderate vulnerability to flooding. This flooding could have major consequences for the complex. Therefore, the complex is at a high risk due to flooding, as seen in Table 12.

Likelihood	Consequence				
	1.Catastrophic	2.Major	3.Moderate	4.Minor	5.Insignificant
A. Very likely	1A	2A	3A	4A	5A
B. Likely	1B	2B	3B	4B	5B
C. Medium	1C	2C	3C	4C	5C
D. Unlikely	1D	2D	3D	4D	5D
E. Very unlikely	1E	2E	3E	4E	5E

Table 12: Risk assessment for the Rowes Wharf Complex

4.4) Vulnerabilities and Consequences to Flooding of the Harbor Towers

Finding #4: The Harbor Towers are at moderate to high vulnerability to flooding. Flooding could have major consequences. Overall, they are at high risk due to flooding.

4.4.1) Vulnerable Features of the Harbor Towers

Our surveying route for the Harbor Towers involved taking measurements of the height of the higher and lower seawalls, the opening to an air vent leading to the basement, the main entrances to the eastern and western towers, an outside grate leading to service equipment, and outdoor electrical outlets. Figure 19 shows the pathway of this surveying loop. The error of closure for this loop was 0.031 ft. Figure 20 shows pictures taken of the identified vulnerabilities. These pictures include the lower seawall, a vent leading to service equipment in the basement, the main entrance, and the higher seawall. These features are critical to the function of the building.

Harbor Towers
1: Height of seawall (north); 9.652 ft NAVD
2: Height of Towers higher seawall; 12.039 ft NAVD
3: Opening in air vent; 8.711 ft NAVD
4: Patio wall; 11.648 ft NAVD
5: Height of seawall (northeast); 8.220 ft NAVD
6: Top of stairs; 11.491 ft NAVD
7: Main entrance to 65 E. India Row; 11.746 ft NAVD
8: Outside grate leading to service equipment; 11.069 ft NAVD
9: Outdoor outlets in front of trees; 11.235 ft NAVD
10: Main entrance to 85 E. India Row; 11.743 ft NAVD

1→2→3→4→5→6→7→8→9→10→1

Error of closure: 0.031 ft

Figure 19: Surveying route for the Harbor Towers, with key showing measurements and error of closure. (*Google Maps*)

Figure 20: Pictures taken of the vulnerable features of the Harbor Towers (top left: higher seawall, top right: air vent leading to basement, bottom left: main entrance to east building, bottom right: lower seawall)

4.4.2) Vulnerability to Flooding

The building manager, Hugh Schaffer, and the facilities manager, Fran Higgins, from the Harbor Towers, explained the problems that these buildings are facing.

- These buildings are experiencing water damage due to their close proximity to the coast. Even with current sea levels, there has been water intrusion coming up through the floor of the basement. We observed pools of water, salt collections, and rusting in the basement area. The tiles in the floor of the laundry room were also loose due to the water damage.
- The air vent leading from outside to the basement also had leaks that caused futher water seepage into the basement.

- The buildings have recently undergone $1 million worth of grout injections to stop the intrusion of water. However, these efforts have been ineffective and water is still entering the basement, which contains service equipment.
- The main boilers and coolers for the Towers are located in the Harbor Garage, adjacent to the Towers. A vulnerability assessment for the Harbor Garage was completed in *Preparing for the Rising Tide*. The Harbor Garage is at a high risk of flooding and the location of the boilers and coolers affects the residents of the Harbor Towers.

Overall, the Harbor Towers are at a moderate to high vulnerability to flooding. Today's 100-year storm will affect the lower seawall and the air vent opening. The 100-year storm in 2050 is a major concern for these residential buildings, as all of the measured vulnerable features have critical elevations under 12.8 ft NAVD. Table 13 summarizes the flood vulnerability of the Harbor Towers.

Location	Elevation	Vulnerability to flooding
Height of lower seawall	8.220 ft NAVD	High
Opening in air vent	8.711 ft NAVD	High
Outside grate leading to service equipment	11.069 ft NAVD	Moderate
Outdoor electrical outlets in front of trees	11.235 ft NAVD	Moderate
Main entrance to 65 E. India Row	11.746 ft NAVD	Moderate
Main entrance to 85 E. India Row	12.743 ft NAVD	Moderate

Table 13: Vulnerability to flooding for the Harbor Towers

4.4.3) Severity of Consequences from Potential Flooding

The Harbor Towers are already experiencing water damage, and the damage will worsen as sea levels rise. The main generators for the Towers are in the basements and the boilers and coolers are in the bottom of the Harbor Garage. The location of this critical equipment could have major consequences for the Harbor Towers. The building managers for the Towers explained that they do not have any emergency preparedness supplies, including food, water, sandbags, flood shields, and evacuation plans. This lack of emergency preparedness increases the potential consequences that could occur to these residential buildings in a flood. This creates problems for post-flood recovery, which is an example of an indirect and intangible consequence. The buildings are at moderate to high vulnerability and there could be major consequences. Overall, the Harbor Towers are at a high risk due to flooding, as seen in Table 14.

Likelihood	**Consequence**				
	1.Catastrophic	**2.Major**	**3.Moderate**	**4.Minor**	5.Insignificant
A. Very likely	1A	2A	3A	4A	5A
B. Likely	1B	2B	3B	4B	5B
C. Medium	1C	2C	3C	4C	5C
D. Unlikely	1D	2D	3D	4D	5D
E. Very unlikely	1E	2E	3E	4E	5E

Table 14: Risk assessment for the Harbor Towers

4.5) Vulnerabilities and Consequences to Flooding of the Christopher Columbus Park

Finding #5: The Christopher Columbus Park is at low to high vulnerability to flooding. Flooding would have only minor consequences. Overall, it is at low risk due to flooding.

4.5.1) Vulnerable Features of the Christopher Columbus Park

Our surveying route for the Christopher Columbus Park involved taking measurement points of the height of the seawall, the electrical boxes near the dock, and the trellis walkway. Figure 21 shows the pathway of this surveying loop. The error of closure for this loop was 0.066 ft. Figure 22 shows pictures taken of the identified vulnerabilites of the site. The pictures include the trellis walkway, the electrical box, and the seawall because these features are critical to the function of the park.

Christopher Columbus Park
1: Top of stairs (outside Harbor Towers); 11.491 ft NAVD
2: Corner of Milk Street; 9.285 ft NAVD
3: Corner of Central Street; 9.391 ft NAVD
4: Light post on corner of State Street; 9.533 ft NAVD
5: Top of steps leading to walkway at park; 14.587 ft NAVD
6: Statue at highest point of park; 13.800 ft NAVD
7: Height of park seawall; 8.357 ft NAVD
8: Electrical boxes on dock; 9.591 ft NAVD
9: East Long Wharf; 8.720 ft NAVD
10: South Long Wharf; 8.155 ft NAVD
11: Duck Boat parking; 8.625 ft NAVD

1→2→3→4→5→6→7→8→9→10→11→1

Error of closure: 0.066 ft

Figure 21: Surveying route for the Christopher Columbus Park, with key showing measurements and error of closure. (*Google Maps*)

Figure 22: Pictures taken of the vulnerable features of the Christopher Columbus Park (left: trellis walkway, middle: electric boxes near dock, right: height of seawall)

4.5.2) Vulnerability to Flooding

The park has varying levels of vulnerability to flooding. The critical components, including the height of the seawall and the electrical boxes near the dock, are at high vulnerability to flooding due to their low elevation and close proximity to the water. The higher elevated areas at the trellis walkway and the statue of Christopher Columbus are at lower vulnerability. The low-lying areas of the park and the electrical boxes could flood during today's 100-year storm. Certain parts of the higher elevated areas could be affected by the 100-year storm in 2100, but will likely not be affected by sea levels in the foreseeable future. Table 15 summarizes the vulnerability of the Christopher Columbus Park to flooding.

Location	**Elevation**	**Vulnerability to flooding**
Height of seawall	8.357 ft NAVD	High
Electrical boxes on dock (outside Marriott Hotel)	9.591 ft NAVD	High
Christopher Columbus statue	13.800 ft NAVD	Moderate
Trellis walkway	14.587 ft NAVD	Low

Table 15: Vulnerability to flooding for the Christopher Columbus Park

4.5.2) Severity of Consequences from Potential Flooding

Areas along the coastline of the park are at a high vulnerability to flooding, while the higher elevated areas are at low vulnerability. There could be minor consequences due to the lack of critical equipment in the park. The electrical boxes near the dock are at high vulnerability, but they only supply electricity to the outdoor light posts. The area behind the seawall is at high vulnerability due to the low elevation, but there are only grass areas and sidewalks. Flooding of this environmental property near the seawall would be an example of a direct and tangible consequence. Overall, the Christopher Columbus Park is at a low risk due to flooding, as seen in Table 16.

Likelihood	Consequence				
	1.Catastrophic	2.Major	3.Moderate	4.Minor	5.Insignificant
A. Very likely	1A	2A	3A	4A	5A
B. Likely	1B	2B	3B	4B	5B
C. Medium	1C	2C	3C	4C	5C
D. Unlikely	1D	2D	3D	4D	5D
E. Very unlikely	1E	2E	3E	4E	5E

Table 16: Risk assessment for the Christopher Columbus Park

4.6) Short-Term and Long-Term Resilience Strategies for Flooding

Finding #6: Building-specific strategies can be effective in increasing resiliency in both the short and long term.

Building-specific strategies can be effective in increasing resiliency to flooding caused by annual storms and 100-year storms. Strategies that have been used in other cities and buildings are summarized as follows, with detailed information in Appendix A.

- Create emergency preparedness plans
- Add flood sealants

- Install flood shields
- Raise or relocate critical equipment
- Improve building materials
- Raise seawalls
- Raise dock posts

For numerous buildings, short-term and long-term strategies can be applied in order to reduce the damage of flooding and increase the resiliency of a site. Short-term strategies are effective in the events of a current annual storm and 100-year storm. For example, emergency preparedness plans are an effective short-term strategy in order to protect a site from serious flood damage. Although this strategy is not a permanent solution to reduce the effects of flooding, emergency preparedness can help a building survive and remain operational after a storm. Emergency preparedness plans can include the use of pumps, which could be used to help remove flood waters from the building. Also, backup generators or power sources are critical in the event of a storm; therefore, maintaining this critical equipment is important to power other critical equipment in the building.

Other short-term strategies that could be applied on a site-specific level are flood sealants and flood shields. Sealants can be installed along openings of structures, including doors, windows, and cracks, in a variety of locations. Flood shields, permanent or temporary, can keep water away from critical areas in a building. These areas could contain critical equipment, such as generators, and it is vital to keep water away from this equipment during flood events.

However, both of these strategies can have negative impacts. Sealants can cause an increase in water pressure in other areas of the building, since the water can no longer enter the building through the original openings. Similar to sealants, flood shields can cause water to be redirected into other areas of the building.

As the threat of flooding increases, buildings have to research long-term strategies. Raising critical components of a building is an effective strategy to increase resilience, so that it is above projected sea level rise. Another effective option could be to evacuate the first floor of a building, so that all critical equipment and services are above flood levels. However, these site-specific strategies may not be effective in the long term as sea levels continue to rise and affect entire neighborhoods. Both building-specific and neighborhood strategies can be used to address these effects.

4.7) Neighborhood Resilience Strategies

Finding #7: Neighborhood strategies can be combined to increase the resilience of areas against flooding caused by climate change.

Most neighborhood strategies are large scale and long-term, designed to change the topography of the area. These strategies are as follows, with more information found in Appendix A:

- **Floodable public space:** Below-grade public space can function as a recreational area for the community. During a flood event, water can be redirected to this space to take pressure off of the urban water system.

- **Improve seawalls and roads:** Seawalls can be improved to redirect water to specific locations that will cause less damage to the community. Roads can also be raised so that they can still be used during a flood, and they can be sloped away from buildings so that water is redirected to below-grade areas.
- **Install permeable pavement and drainage systems:** Permeable pavement can be used to redirect floodwater to a new location such as a retention pond or another drainage system.

A main idea of implementing neighborhood strategies is the creation of below-grade floodable zones, which could in turn protect buildings at higher elevations. Seawalls could be improved to redirect water to these floodable zones. These seawalls must be effective but also have a tourist appeal. Other ways to redirect floodwaters include permeable pavement, raised roads, and drainage systems. Although directing water to below-grade public spaces can help reduce flood damage to buildings, toxic contaminants could be picked up by the flood waters, causing a health risk to the community. To prevent these consequences, a filtration system could be installed along the public waterways.

4.8) Combination of Neighborhood Resilience Strategies

Finding #8: It is not feasible for the neighborhood of Downtown Boston to employ a single resilience strategy to reduce its risk of flooding.

Due to climate change, sea levels are projected to rise two feet by 2050 and six feet by 2100. This volume of water exceeds the capacity of any single resilience strategy. To be effective against this volume of water, resilience strategies can be combined. Combined neighborhood strategies, such as permeable pavement leading to a below-grade public space, can accommodate larger volumes of water. To protect Downtown Boston, paired capacity investments can be implemented to reduce the damage of potential flooding. This concept involves constructing an at- or above-grade structure with below-grade open space that diverts water away from vulnerable sites in the neighborhood (TBHA, 2013). The combination of neighborhood strategies changes the topography of Downtown Boston to protect critical areas.

4.9) Considerations and Factors Affecting the Implementation of Strategies

Finding #9: There are many considerations and factors that affect the feasibility of the implementation of these strategies in urban areas.

There are many considerations and factors that affect the implementation of these strategies to urban areas. These considerations can be categorized as follows.

- Negative financial impacts
- Negative impacts on aesthetics
- Degradation of materials
- Unintended negative impacts

4.9.1) Negative Financial Impacts

The cost of implementing these strategies can be expensive, thus inhibiting their implementation. Depending on the budget of the financer of the building or neighborhood, some strategies can be eliminated as possibilities due to high costs. It can be more cost effective to integrate strategies into new construction rather than retrofitting them later. Several strategies are available at minimal cost, some are available at a moderate cost, and some are large-scale, expensive strategies (Green Ribbon Commission, 2013). These strategies are organized by cost in Table 17 and references for these costs can be found in Appendix A**.** An example of a strategy from each column follows the table.

Minimal Cost Strategies	**Moderate Cost Strategies**	**Large Scale, Expensive Strategies**
Protect/cover service equipment	Raise roads	Expand drainage system
Secure objects during storms	Apply sealants	Separate sewage and water lines
Obtain hard copies of emergency lists (tenants, floor plans, etc.)	Create rain gardens	Construct dikes
Keep emergency supplies stocked (food, water, backup generator)	Install permeable pavement	Combination of waterways and levees
	Raise buildings	Apply beach nourishment
		Build underground water storage chambers
		Create living shorelines

Table 17: Flood resilience strategies organized by low, moderate, and high cost

An example of a minimal cost strategy is obtaining hard copies of emergency lists, as part of an emergency preparedness plan. If a residential building loses power, it is crucial for the building owner to have a hard copy list of all tenants in order to make sure that everyone is evacuated during an emergency situation. An example of a moderate cost strategy is applying sealants. Sealants can be used to fill cracks or to surround door and window frames to prevent cracking. This helps prevent water from entering a building and causing damage during a flood event. An example of a large-scale, expensive strategy is building an underground water storage chamber. This chamber could take a long time to construct, and it would need to be retrofitted for salt water since it is highly corrosive.

4.9.2) Negative Impacts on Aesthetics

Aesthetics are another important aspect to consider before choosing a strategy to implement. Downtown Boston includes many historic areas and is a large tourist attraction. Careful planning and thoughtfulness must occur when choosing a strategy, as to not select one that will detract from the scenery. Strategies that effectively increase resilience while maintaining aesthetics will impact the area positively.

An example of a strategy detracting from aesthetics is the use of a seawall. Raising a seawall could help to protect neighboring buildings, but it could also detract from the scenery by obstructing the view of the ocean. This could make the resilience strategy less desirable. Aesthetics could also be an issue when creating retention ponds or floodable public space. If combined sewage overflow is present in the city, there could be sewage aboveground in public areas during a flood event.

4.9.3) Degradation of Materials

The topic of salt water corrosion on materials was mentioned several times during our expert review panel. A number of the experts informed us that areas designated for flooding can only be flooded so many times. Eventually, salt and pollution from the water could destroy the materials, resulting in the potential need to reconstruct the area. Many materials can be coated with a water-resistant layer or sealant in order to protect them for a few years from such damages.

4.9.4) Unintended Negative Impacts

Some strategies can have unintended negative impacts. As stated above, some can detract from the aesthetics of the area or be damaged when exposed to salt water. Other negative impacts caused by resilience strategies could include the following:

- Health impacts from raw sewage in public areas when stormwater floods in high volumes due to combined sewage overflow. Another health impact is that open floodwater can be a breeding ground for mosquitoes, possibly carrying the West Nile virus (EPA, 2012).
- Cultural impacts due to changing historic and heavily-used public areas.

Other specific examples of different effects of flooding can be found in Background chapter 2.2.

4.10) Stakeholders' Knowledge of Climate Change and Resilience Strategies

Finding #10: Overall, stakeholders of buildings in Downtown Boston understand the threat of flooding due to climate change. However, there is a lack of knowledge about strategies that can be implemented to increase resilience flooding.

All of the building stakeholders that we spoke with were willing to give us information on their buildings and discuss the issue of climate change. They all had an understanding of climate change and the potential effects that it could have on their building. For example, we spoke with the building manager of the Rowes Wharf Complex, Joe Gibbons, and he expressed concern for the underground service equipment in the garage. He was aware that Boston was fortunate to be at low tide during Superstorm Sandy, and he stated that he knew his building could have been severely damaged if Sandy had hit at high tide. The facilities manager and building manager of the Harbor Towers also expressed that they felt fortunate that the buildings were not severely damaged during this storm. These stakeholders of the Harbor Towers were also informed about the effects of climate change because the buildings have experienced issues with flooding and water intrusion.

Although these stakeholders understood the effects that climate change could have on their buildings, they expressed a lack of knowledge regarding how to address these effects. The building manager at the Harbor Towers, Hugh Schaffer, discussed the use of grout injections in the basement that failed to prevent flooding. Due to a lack of knowledge of resilience strategies that could be used to address this issue, the building manager has not implemented any successful strategy to reduce flooding in the basement. Overall, the stakeholders in this area were eager to receive our recommendations for resilience strategies to be implemented at their building sites.

4.11) Summary of Findings

Our project team completed risk assessments for the five buildings in our study area by assessing these buildings' vulnerability to flooding and the potential magnitude of the consequences. Following these assessments, we identified strategies that could be effective in increasing the resiliency of buildings in coastal cities. We also identified factors that affect the implementation of these strategies to coastal cities and the general understanding that building stakeholders have of these strategies. Our recommendations based on these findings can be found in the next chapter.

5) Conclusions and Recommendations

The goal of our project was to determine the vulnerability of Downtown Boston to sea level rise and storm surge and provide recommendations to the Boston Redevelopment Authority on strategies to increase resiliency against those threats. Using surveying equipment, our team was able to conduct vulnerability assessments on James Hook Lobster Company, the Coast Guard Building, the Rowes Wharf Complex, the Harbor Towers, and the Christopher Columbus Park. Using these vulnerability assessments along with specific information provided to us by building managers, we were able to determine the risk of each building due to flooding. We then identified potential resilience strategies and we examined their strengths, weaknesses, and feasibilities. Our final recommendations were submitted to the Boston Redevelopment Authority in their efforts to revise the Municipal Harbor Plan.

In this chapter, we begin by presenting our building specific strategies for the five sites in our study area that were not assessed in *Preparing for the Rising Tide*. We then present our recommendations for neighborhood strategies followed by recommendations for addressing the negative consequences of these strategies. We conclude this chapter by discussing the limitations of our research and provide recommendations for future considerations.

5.1) Implement Building-Specific Strategies

Based on our vulnerability assessments, we made recommendations for our five sites. In the following sections, we recommend short-term and long-term strategies for each specific site.

5.1.1) Recommendations for James Hook Lobster Company

Due to the fact that all measured components are above today's 100-year storm level, as stated in Finding #1, James Hook Lobster Company is at low risk due to flooding associated with sea level rise. To address this risk, we recommended the following:

Short-term Strategies:

- **Create Emergency Preparedness Plans:** We recommend that James Hook Lobster Company create emergency preparedness plans that include a plan for covering service equipment to protect it from water damage.
- **Apply Flood Sealants**: We recommend that waterproofing sealants are applied to the foundation of James Hook Lobster Company, and the walls are coated with acrylic waterproofing paint.
- **Install Flood Shields**: We recommend that temporary flood shields be installed on site for all windows and doors during flood events. Since James Hook Lobster Company is at low risk, we do not find it necessary to install permanent flood shields.

Long-Term Strategies:

James Hook Lobster Company is a temporary building that will be replaced by the time that the site is at a higher risk of flood damage. Therefore, we do not have any long-term strategy recommendations for the current building.

5.1.2) Recommendations for the Coast Guard Building

As stated in Finding #2, the Coast Guard Building is at a moderate vulnerability to flooding and there could be major consequences due to the location of service equipment. In order to address this risk, we recommend the following:

Short-Term Strategies

- **Create Emergency Preparedness Plans:** We recommend that, if currently absent, the Coast Guard Building create an emergency preparedness plan that includes a strategy for covering service equipment before a storm, namely the HVAC system along the waterfront. Attention to the HVAC system is necessary because the equipment is at moderate vulnerability to flooding, and it is critical for the function of the building.
- **Apply Flood Sealants:** We recommend that flood sealants be applied to the foundation of the building in order to protect it from water damage. We also recommend that the sealants be applied to the seawall in front of the building in order to protect the wall from being damaged by salt water corrosion.

Long-Term Strategies:

- **Improve the Seawall:** Along with using waterproofing sealants to prolong the life of the concrete, we also recommend that the Coast Guard Building improve the seawall to direct floodwaters into below-grade spaces.
- **Raise or Relocate HVAC System:** We recommend that the Coast Guard Building raise the wall in front of the HVAC system and raise the system itself farther off the ground. This service equipment is critical to the function of the building, so we recommend that steps be taken now to protect it, even though the system will not be affected by today's 100-year storm. In the long-term, we recommend that the system be completely relocated away from the waterfront.

5.1.3) Recommendations for the Rowes Wharf Complex

The Rowes Wharf Complex is mostly at moderate vulnerability to flood damage caused by sea level rise, as stated in Finding #3. There could be major consequences due to the service equipment being located underground. We recommend the following strategies for the Rowes Wharf Complex.

Short-Term Strategies:

- **Cover and Divert Water from Vent:** The vent outside the parking garage leads directly to the generator, located three stories underground. The elevation of the vent puts it at moderate vulnerability to flooding, so we recommend that the Rowes Wharf Complex take action now to make this area more resilient. We recommend that the complex have a short-term plan to cover the vent during extreme weather events.

Long-Term Strategies

- **Seal and Relocate Vent:** In the long-term, we recommend that the vent leading to service equipment be sealed off to keep water out the garage because the generator is located below the vent.
- **Raise Seawall:** We recommend that the seawall be raised in order to accommodate for rising sea levels. This will help keep water away from the Rowes Wharf Complex for a longer period of time.
- **Raise Dock Posts:** We recommend that the dock posts be raised, even though they are not in any immediate danger. The dock posts are currently at a low vulnerability to flooding, but there could be major consequences if flooding occurred.
- **Relocate or Raise all Critical Equipment:** All service equipment and backup service equipment is located underground in the parking garage. In the short-term, we recommend that all of the service equipment be elevated off the ground, to allow for some flooding in the room. In the long-term, we recommend that all service equipment be relocated to another story of the building with a lesser risk of flooding.
- **Install Permeable Pavement:** We recommend that the brick plaza pathways be replaced with permeable pavement during the remodel. While this pavement will not have the capacity to completely prevent flooding, it can be used to divert some water away from the complex, purposely redirecting it to a below-grade area.

5.1.4) Recommendations for the Harbor Towers

As stated in Finding #4, the measured components at the Harbor Towers are all at moderate to high vulnerability to flooding caused by sea level rise. Due to the location of critical equipment, there could be major consequences. In order to minimize this risk and make the two buildings more resilient to flood damage, we recommend the following strategies.

Short-Term Strategies

- **Create Emergency Preparedness Plans:** We recommend that the Harbor Towers create and implement emergency preparedness plans immediately. The plans should include a means of covering all service equipment to protect it from water damage during a flood, and the building should have sandbags on-site to protect doors and other openings during a severe storm.
- **Seal the Basement and Waterproof the Concrete:** We recommend the use of a silicate-based concrete sealant to help prevent water from entering the basement and causing damage. Sealants can also be used around the foundation of the building and along the concrete seawalls.
- **Raise the Outdoor Outlets:** The outdoor outlets located next to the trees outside of the buildings are at moderate vulnerability to flooding. We recommend that these outlets be raised to reduce the risk of damage, and they should also include a waterproof cover for when they are not in use.
- **Install French Drains:** We recommend that French drains be installed in the grass alongside the buildings to redirect some floodwater. These drains will not be able to

accommodate a large volume of water, but in combination with other flood resilience strategies, they will help divert water away from the buildings.

Long-Term Strategies:

- **Raise Seawalls:** The seawalls in front of the Harbor Towers are at high vulnerability to flooding, so we recommend that the walls be raised as soon as possible. This will help prevent the property from flooding for a longer period of time.
- **Relocate or Raise HVAC:** The grate outside of the Harbor Towers that leads to all of the service equipment for each building is at moderate vulnerability to flooding. We recommend that in the short-term, the HVAC system and other service equipment be elevated to allow for some flooding in the room. In the long-term, we recommend that this equipment be raised to another story of the building where it is at less of a risk for flooding.

5.1.5) Recommendations for Christopher Columbus Park

As stated in Finding #5, the critical components of Christopher Columbus Park are at high vulnerability to flooding caused by sea level rise, but the consequences of the park flooding could be minor. We recommend the following to minimize the consequences and increase the resilience of the park as a whole.

Short-Term Strategies

- **Move or Raise the Electrical Equipment:** The electrical box on the dock is at high risk due to flooding. We recommend that immediate action be taken due to the high level of risk along with the hazard that it poses. We recommend that the electrical box be elevated for now so that the risk of flooding is reduced, and in the long-term it should be relocated. The importance of this equipment makes it worth the cost of relocation, as discussed in Finding #8.

- **Lower the Drains on the Walkway:** We observed that the drains located on the trellis walkways were not level with the surrounding bricks, so water was pooling around them. We recommend that these drains be lowered in order to improve the effectiveness of the park's drainage system.

Long-Term Strategies

- **Install a Rain Garden or Retention Pond: W**e recommend that the park be used as space to redirect floodwaters. We recommend that a rain garden or retention pond be installed in the park, as this could provide an aesthetic attraction to the park while taking some pressure off of the water system. These two strategies alone will not prevent the area from flooding, but they could make an impact when paired with other strategies.
- **Raise the Seawalls:** The seawall at the Christopher Columbus Park is at high risk due to flooding, so we recommend that this wall be raised to protect nearby critical equipment.
- **Install Permeable Pavement:** We recommend that the walkways of the park be replaced with permeable pavement that can redirect the water to another location. These pathways could potentially lead to a rain garden or retention pond, as previously suggested.

5.2) Implement Neighborhood Strategies

As discussed in Finding #7, neighborhood flood resilience strategies are an effective means of increasing resiliency in urban areas. Projected flooding, due to sea level rise, increases over time. Therefore, building-specific strategies alone will not be able to protect the individual sites from flood damage. Large-scale neighborhood strategies can accommodate larger volumes of water as projected flooding increases over time. These strategies are expensive and take a long time to implement due to their large-scale construction. Therefore, all of the neighborhood strategies are categorized as long-term strategies.

We recommend that these strategies ultimately be combined to alter the topography of the city, as described in Finding #8. The strategies are:

- **Create Below-Grade Public Space:** We recommend the use of floodable public space. This below-grade space could be used for recreational purposes and water could be redirected there during a severe storm.
- **Install Drainage Systems:** We recommend the use of drainage systems such as permeable pavement or French drains to collect water and redirect it to a new location, such as a retention pond.
- **Raise and Slope Roads:** We recommend that roads be raised above the projected elevation of sea level rise so that they are still usable. We also recommend that a sloped grade be added to roads and sidewalks so that they can redirect water away from buildings and purposely guide it to a new location that is safer to flood.
- **Construct Underground Water Storage:** We recommend that water be temporarily stored underground before being filtered and returned to the ocean.

5.3) Integrate Strategies into New Construction

We recommend that major construction or renovation efforts integrate resilience strategies from the start, rather than being retrofitted later.

This approach could reduce expenses. As discussed in Finding #9, expenses are a limiting factor in implementing resilience strategies. For example, the Big Dig could have been used as below-grade water storage, but retrofitting the tunnels to withstand saltwater could be more difficult and expensive now.

5.4) Avoid Negative Consequences of Strategies

As discussed in Finding #9, there are several downsides to resilience strategies that will make them less desirable or not possible to be implemented.

We recommend that future research be conducted on the use of these strategies at specific locations, regarding the following issues:

- **Negative impacts on aesthetics**: Strategies with a negative impact on the aesthetics of the area will be less desirable for the community. An example of this is raising a seawall, because it obstructs the view of the ocean. We recommend that research be done on public opinion of strategies before implementation in order to successfully increase the resilience of the area while maintaining the scenic attraction.

- **Degradation of materials**: Certain strategies may be difficult to implement due to the materials that they require. Since salt water is highly corrosive, materials such as concrete used in seawalls will be worn down over time if they are not consistently coated with a water resistant sealant. This would require additional upkeep, and the seawalls would need to be repaired or replaced if they were not kept correctly. We recommend that research be done on the best materials and sealants to use on specific strategies before implementation.
- **Negative financial impacts**: Some strategies, such as creating underground water storage, could be very costly and could possibly put financial strain on the community. We recommend that a detailed cost analysis be done before implementing a strategy, and it will be necessary to determine where funding is coming from.
- **Negative impacts on surrounding areas**: Some structures can have a positive impact on the immediate surrounding area, while having a negative impact on other areas. For example, a seawall can protect the building that it is built in front of, but this could cause water to flood surrounding areas. We recommend that all possible impacts of a strategy be studied and understood before implementation.
- **Long timetables for communities**: Implementing some strategies could take a long period of time, and this could be undesirable for the community. For example, an underground water storage facility could be under construction for a long period of time. We recommend that the timeline of implementing strategies along with public opinion of that timeline be understood before implementation.

5.5) Inform Building Stakeholders about Resilience Strategies

As stated in Finding #10, we found building stakeholders to generally understand the potential effects of climate change to their buildings. However, they were not informed about resilience strategies to address these effects. We recommend that building stakeholders understand the vulnerability of their building to flooding caused by climate change, and we also recommend that they understand the consequences of flooding to specific components in their buildings. There needs to be collaboration between city organizations and building stakeholders to address these vulnerabilities and potential consequences. We recommend that the Boston Redevelopment Authority, The Boston Harbor Association, and other advocacy groups inform building stakeholders on potential resilience strategies for their building sites and surrounding areas.

5.6) Limitations to Research and Recommendations for Future Considerations

As discussed in Finding #9, there are many considerations and factors that affect the implementation of our suggestions in Downtown Boston. Our project was limited in scope and time, so there are gaps of knowledge that need to be addressed. We identify four limitations to our study and make recommendations to address them.

First, our main limitation was the scope of our research. We only examined our study area in Downtown Boston, and we did not have the capability to model how our recommendations could affect the surrounding neighborhoods. We did not study the power grids or electrical lines that affect the study area, and these lines could affect the critical elevation of individual building's service equipment, depending on where they connect.

We recommend that future researchers examine Boston as a whole in order to provide the most effective resilience strategy recommendations.

Our second limitation in research was our use of sea level rise and storm severity predictions. The predictions that we use only consider static water levels, so wind and wave action are not accounted for. We also were not able to create a 3D model of water or land elevation, so our recommendations are based solely on the points that we measured during our surveying. Therefore, our categorization of low, moderate, and high risk can be misleading in some cases because we did not have the tools to model all factors of climate change.

We recommend that these factors should be taken into account to give a more accurate timeline on when resilience strategies should be implemented.

Third, we lacked access to the Coast Guard Building. We were not allowed inside due to security reasons, so we did not have any information regarding the location of internal service equipment.

We recommend that a more thorough vulnerability assessment be conducted in the future since our recommendations for that building are only based on our measurements of the surrounding area.

Fourth, we based our cost estimates on similar projects, but the actual cost of implementing these strategies will vary. We also did not eliminate any of our recommendations based on cost because we were not given any budgets for implementing strategies on these buildings. It was also not decided where funding would come from, so we were unable to make decisions about feasibility based on cost.

We recommend that a cost assessment be conducted for each recommendation on each individual building in order to obtain more accurate figures.

5.7) Conclusion

Sea level rise and increased storm severity due to climate change pose serious threats to the Downtown Boston waterfront. In Boston, sea levels are projected to rise two feet by 2050 and up to six feet by 2100, and precipitation is expected to increase along with increased severity of storms. Sea level rise, increased precipitation, and increased storm severity put buildings and neighborhoods in the Downtown Boston area at risk for flooding, which can cause severe consequences. It is possible to reduce this risk of damage by implementing resilience strategies. There are effective strategies that can be used to decrease vulnerability to flooding caused by sea level rise and storm surge in both the short term and long term. The study done in *Preparing for the Rising Tide* assessed the vulnerability of buildings along the waterfront and proposed resilience strategies. Our team assessed vulnerability of the remaining buildings in the Downtown Boston area, not previously completed in the report. We then proposed recommendations, with expert feedback, for resilience strategies for specific buildings and for the entire area. These recommendations were compiled into a memo and presented to the Boston

Redevelopment Authority. The recommendations can be used as a platform to build upon as the Boston Redevelopment Authority revises the Municipal Harbor Plan for the Downtown Boston area. These recommendations can also be applied to other coastal cities throughout the world.

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Appendix A: Further Information on Strategies Described in Report

Emergency preparedness strategies

There are a number of precautions that building managers should take during severe weather and flooding. Released on January 22, 2013, *Emergency Preparedness: Lessons Learned From Superstorm Sandy* describes steps that building facilities should plan (NYC.gov, 2013). Included in these recommendations are:

- set up an emergency area of refugee for employees and residents
- make hard copies of emergency lists of all employees or residents
- make procedures for securing all objects before storms, including patio furniture, docks, and other objects on lawns of buildings
- protect and cover all critical service equipment
- maintain all resiliency equipment on an annual basis (NYC.gov, 2013)

The Green Ribbon Commission's Report, *Building Resilience in Boston*, also gave recommendations of supplies that building managers should have during storms and flooding:

- emergency food and water supplies, depending on the number of employees or residents in the building
- backup generators or a backup power source to maintain electricity for critical equipment
- pumps to remove water from basements and away from critical equipment

- sandbags and other water diversion techniques to protect low lying floors (Green Ribbon Commission, 2013)

To prepare buildings for severe weather, building managers should also make sure that their insurance coverage is up to date with current flood plains. This will expand insurance coverage and reduce costs of repairs after storms (Consumer Reports, 2013).

Flood sealants and shields

Dry flood-proofing involves using different strategies to prevent the inflow of water into buildings, including sealants and shields. Sealants are products that are sprayed or coated onto buildings to make them watertight. These can be applied around windows, doors, and any other openings into a building (FEMA, 2006). Sealants can consist of:

- concrete waterproofing coatings that adhere to concrete and masonry walls, costing between $30 and $40 per 100 square foot
- silicate-based concrete sealers that cost between $40 and $50 per 100 square foot
- acrylic waterproofing paint that costs $35 per 75 square feet (Huber, 2012)

Grout injections are also examples of flood sealants. Hydrostatic grout is injected into cracks in the sides of buildings, where it reacts with water to expand (McPherson, 2012)). These injections permanently seal cracks and further sealants are coated over the grout for further floodproofing. The problem with these sealants and injections is that while they seal certain parts of buildings, water pressure can still cause leaks in other areas of the building (McPherson, 2012).

Flood shields include panels, doors, and gates that are used to close off large sections from the inflow of water (Jones, 2009). These can be permanent fixtures to a building or can be temporarily installed during flooding. It is important to follow all of the codes outlined by the US Army Corps of Engineers, the National Nonstructural/ Flood Proof Committee, and FEMA's Mitigation Assessment team when installing these shields (Jones, 2009). These shields should be installed to the structure of the building and not to weak areas. They should also be strong enough to withstand the hydrostatic load of floodwater (Booth, Hammond, Lamond, Proverbs, 2012). An example of a flood shield is shown in Figure 23. Flood shields are available in sizes ranging from 10 inches to 36 inches (Zero International, 2008). They range in price between $150 and $400 per unit (FEMA, 2013).

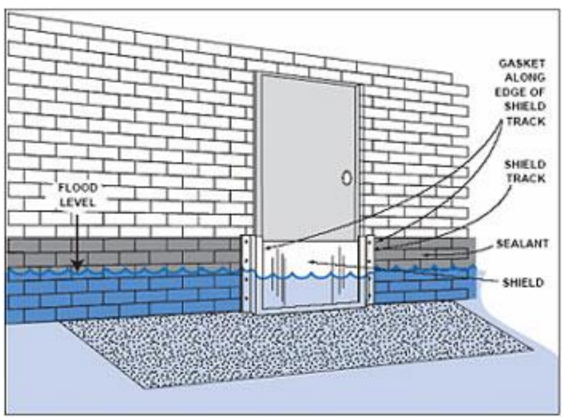


Figure 23: Example of a flood shield to protect doors (Jones, 2009)

Backflow valves for sewage management

A major issue when flooding occurs is the backflow of sewage into buildings. Backflow occurs when water levels rise above a building's drain, damaging pipes and leading to health hazards. This can be prevented with the installation of valves that only allow one-direction water flow. There are two types of valves that can be installed, a gate valve or a flap/ check valve (FEMA, 2011). These can have simple or complex designs. A gate valve is a manual valve that requires the owner to turn the valve, stopping flow in the pipe. Flap or check valves are automatic, meaning that they close when flow in the pipe begins to reverse. These automatic valves have air in an expansion chamber that is compressed by sewer backup, causing a knife gate to rise until the valve is closed (FEMA, 2011). Once water levels reside, a counterweight at the top of the expansion chamber forces the trapped air out of the chamber, lowering the knife gate and restoring flow. Flap or check valves are usually weaker than gate valves, but do not require the owner to operate them (Jay R. Smith Mfg. Co., 2010). There are also some combinations of gate and flap/ check valves that have automatic closing systems for a gate valve. Figure 24 shows the typical installation for an exterior backflow valve.

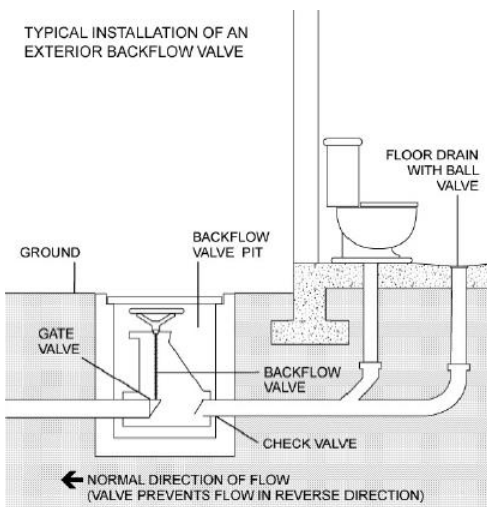


Figure 24: Typical installation for an exterior backflow valve (FEMA, 2011)

To ensure an entire building is protected, all drain pipes in the building need backflow valves. This includes washing machine pipes and sewer or septic tank connections (FEMA, 2011). A licensed plumber or contractor needs to install these valves to make sure they are properly installed and meet building codes. A typical flap or check valve, including installation costs, will cost approximately $600 and a more complicated combination valve will cost approximately $1,400 (FEMA, 2011). Owners must test and practice opening the valves every 3 months, to ensure that they are working properly (Jay R. Smith Mfg. Co., 2010). They also require occasional cleaning.

Many cities have begun to urge residents to install backflow valves into their homes and businesses that are in flood zones. The city of Toronto has enacted the Basement Flooding Subsidy Program, which pays a subsidy of up to $3,200 per household for backflow valves (MacLeod, 2008). The city of Worcester, Massachusetts also has a subsidy act to protect properties from sewage backup, created by the Department of Public Works and Parks. The Act pays a subsidy of $2,000 per household to install backflow valves (Moylan, 2012). Recently, there have been efforts to expand this subsidy to include businesses in Worcester. Backflow valves are proven to protect property owners from sewage backflow, prompting many cities to provide funding for residents.

<u>Flood-resistant building materials</u>

Flood-resistant material is, “any building material capable of withstanding direct and prolonged contact (at least 72 hours) with floodwaters without sustaining significant damage (requires more than cosmetic repair),” as defined by FEMA (FEMA, 2005). Examples of flood-resistant materials include naturally decay-resistant or pressure-treated lumber, concrete, masonry, corrosion-resistance coated structural steel, and insulation. Table 18 lists materials and suggested location of use.

Location to Use Material	Name of Materials
Beams	• Lumber (Naturally decay-resistant or preservative treated) • Glue-laminated products
Decking	• Lumber (Naturally decay-resistant or preservative treated) • Composite wood members (recycled sawdust and plastic)
Doors	• Hollow metal
Exterior Sheathing	• High-capacity shearwall sheathing ("Exterior" rating)
Flooring	• Latex • Clay • Concrete tile • Rubber sheets/tiles • Vinyl tile • Lumber (Naturally decay-resistant or preservative treated)
Foundation Walls	• Reinforced concrete
Framing	• Lumber (Naturally decay-resistant or preservative treated)
Insulation	• Foam
Piers	• Reinforced concrete
Piles and Posts	• Lumber (preservative-treated)
Siding	• Vinyl • Lumber (Naturally decay-resistant or preservative treated)
Subflooring	• Plywood rated "Exposure 1" or "Exterior"
Trim	• Stone • Steel • Rubber
Walls and Ceilings	• Cement • Brick • Metal • Cast stone (waterproof mortar) • Clay tile • Lumber (Naturally decay-resistant or preservative treated)

Table 18: Flood Resistant Materials

Increasing vegetation

Strategically placed vegetation is another method of flood resilience. While vegetation will not significantly impact the volume of water, it can reduce the velocity. Decreasing the speed of running floodwaters will in turn reduce the damage that they may cause (Department of Environment and Heritage Protection, 2012). Spaulding Rehabilitation Hospital in Charlestown, MA serves as an example of this method. The hospital has vegetation on the roof to slow down storm water runoff during heavy precipitation (Healthcare Facilities Today, 2013). The Municipal Harbor Plan intends to use similar strategies throughout the waterfront.

Breakaway walls

Breakaway walls are a flood resilience strategy that can be used to accommodate pressure from wind or water on the sides of a building. These walls are not part of the structural support of the building, so they collapse when put under 10-20lbs per square foot of pressure without causing any further damage to the building (Town of Holden Beach, 2013). The walls cannot be attached to any utilities or covered by any regular, non-breakaway walls. Otherwise the building will be damaged when the walls give way (South Carolina Department of Natural Resources, 2005). Breakaway walls have been implemented in the Cuisinart Center at Johnson & Wales University in Providence, RI to make the building more resilient to flood damage from the nearby ocean (Daley, 2010).

French Drains

French drains are used as a method of flood resilience that addresses surface water and water that has been absorbed into the ground. These drains are made of perforated piping inserted into a gravel-filled trench that easily collects water and guides it to a new location. (Oklahoma Landscape, Inc., 2012) These drains are useful in preventing water from damaging building foundations, and they are less expensive than most other types of drains (French Property, 2012).

Raised roads

Raising roads is a method of flood resistance that decreases flooding by raising the street level higher than the elevation of predicted floodwaters. Adding a grade to the road could have a similar effect. This strategy has been implemented on Prosser road in Knoxville, Tennessee. This road used to experience annual flooding, presenting an inconvenience and safety hazard to the city. Raising the road above the usual level of floodwater alleviated this issue (Krafcik, 2013). The City of Portsmouth, New Hampshire conducted a cost analysis on raising roads in their report, *Coastal Resilience Initiative*. The cost of raising a road is $30 per lineal foot per foot of height raised. The cost of raising a railroad is estimated at $20 per lineal foot per foot of height raised (City of Portsmouth Planning Department, 2013).

Floodable developments

The idea of floodable developments involves two strategies. The first strategy is to allow water to enter a section of a building, an example of wet waterproofing (Jones, 2009). This strategy is also used as a back-up plan in case other strategies to prevent flood damage fail. The second strategy for floodable developments is to create areas that collect excess water from ocean surges and heavy precipitation (Tam, 2009). Nothing is done to resist flood water from entering buildings. These collections of water can be released into wastewater systems or infiltrated into the ground for urban development projects, such as parks and green roofs (Tam, 2009). However, some negative effects include water pollution with heavy metals, organic chemicals, bacteria, and sediment (Tam, 2009). The water will need to be tested before being used in public projects and its contamination effects will need to be controlled in cities.

A number of cities have used the idea of floodable developments to reduce damage from flooding. Rotterdam, Netherlands has built large parking garages underneath buildings in flood zones to allow water to enter the garages (Higgins, 2012). Museumpark has an underground parking garage with a water storage facility capable of storing 2.6 million gallons of water (Hill, 2013). During severe flooding, vehicles are prohibited from parking in the garages to reduce damage. Water is stored and then pumped into the sewer system when flooding has subsided to reduce sewage overflow. This particular garage cost $11.2 million to construct. There are some possible environmental and safety hazards associated with these flooding garages, such as the flow of chemicals and oil into city streets (Higgins, 2012). Other cities such as Seattle, London, Portland, and San Francisco, collect excess water in cisterns, used later to water wetlands, gardens, green roofs, and parks (Tam, 2009). There have been propositions to create recreational lakes for swimming and boating, used with the water collected in London(Tam, 2009).

The Cheong Gye Cheon Channel in Seoul, South Korea is also an example of a floodable development. This channel was once an elevated highway and a foul-smelling underground waterway. The city worked to change this channel. It is now a social point of the city during dry period and acts as a flood control channel during intense flooding (TBHA, 2013).

Retention ponds

Retention ponds provide a place for excess stormwater during times of flooding. After the initial filling of the pond during storms, the ponds are able to return the water back to the original level slowly over a course of several days naturally. The water either gets insinuated back into the soil or evaporates, which saves areas near the pond from extreme flooding (Canada, 2013). Benefits of retention ponds include removal of select pollutants by plants and bacteria, decomposition of some pollutants, and settling of suspended particulates in stormwater (Raina, 2011).

An example of retention ponds is in Toronto, Ontario. Cost of this retention pond included the following (Raina, 2011):

- One-time installation cost
    - Excavation, \$0.34 per ft^3
    - Earthworks, \$0.11 per ft^3
    - Vegetation \$0.09 per ft^2
- Recurring maintenance cost
    - Landscaping, \$0.19 per ft^2
    - Sediment Removal (Every 10 years), \$0.09 per ft^2
    - Removal Labor, \$120 per hour
- Recurring waste disposal cost
    - Sediment disposal, \$1.70 per ft^3

Rain gardens

Rain gardens are areas of vegetation that help to infiltrate stormwater back into the soil to reduce flooding. In addition to helping increase water infiltration, pollution treatment is also an effect of rain gardens. Plants that do best in rain gardens tend to thrive in both very wet and very dry conditions, which do not need supplemental fertilizer or water once placed into the garden (NEMO, 2013). Cost of rain gardens vary between $5 and $45 per ft^2 depending on type of soil and location of the garden (NEMO, 2013).

Drainage systems and permeable pavement

Drainage systems are also an example of flood resilience. The market area of Charleston, South Carolina is prone to flooding and the city has begun to implement drainage systems to prevent water from damaging buildings. The current system of 5x4 foot drains already in place is not adequately getting rid of excess water. The old brick drains have become filled with sediment and are hard to clean out. This makes the drain system inoperable under full storm surges (Tam, 2009). To combat this issue, the city of Charleston is constructing two 10 ft diameter tunnels of 1200 and 2800 ft as well as a 25 foot diameter main working shaft. A series of 54 drop shafts and an emergency outfall adjacent to existing brick drain will also be added. Precise depths were chosen to avoid sand and silt found immediately below surface and take advantage of the Cooper Marl layer of ground, which has been found to work well for transporting water. Cooper Marl is highly calcareous, medium-to-very-stiff clay sand with a very good stand up time. Charleston is also working on another shaft that is 80 ft deep with each tunnel connecting to each other at that depth, starting construction in 2014 (Robinson, 2012).

Another aspect related to drainage systems that can help reduce the amount of flooding includes getting rid of combined sewer systems. This involves separating the lines specified for sewage and stormwater (Hine, 2012). Ensuring that the sewage system works during times of power outages will also help flood resilience in cities.

Cities such as Gainesville, GA, Calabasas, CA, and Waterford, CT have implemented permeable pavements to be used in connection with drainage systems. This type of pavement consists of concrete pavers with small stones filling the joints that separate the pavers. Water can flow through the joints between the crushed stone layers, which in turn permeates the water back into the soil. In addition to returning the water back into the ground, permeable pavement also filters the water to decrease pollutants (Permeable Paving, 2013). This cleans the water before entering the drainage systems and water pipes within a city. Permeable pavement costs roughly two to three times as much as regular asphalt or concrete, but requires less frequent replacement (Permeable Paving, 2013).

Elevation strategies

Elevating service equipment about the expected level of floodwater is a method of flood resilience. Equipment mounted on a wall, such as sockets, can be placed higher up on the wall in order to avoid water damage. HVAC systems, air conditioners, or other service equipment that is usually placed directly on the ground can be elevated on a platform or placed on another story of the building. (FEMA, 2012). An example of raised service equipment can be found at Spaulding Rehabilitation Hospital in Charlestown, MA. The HVAC system for the hospital is located on the roof in preparation for future flooding (Healthcare Facilities Today, 2013).

Another method of resilience by elevation is raising or evacuating the first floor of a building. The idea behind this strategy is similar to that of raising the service equipment. The first floor of a building is where most flood damage will be incurred, so raising or evacuating that floor will reduce flood damages. Spaulding Rehabilitation Hospital once again serves as an example of this strategy. The main floor of the building is raised one foot off the ground in order to mitigate flood damage (Healthcare Facilities Today, 2013). Another example of this strategy can be found along the Boston Harbor in the Marriott Hotel. The lobby of the hotel has been moved to the second story of the building, making the building more resilient to flooding (TBHA, 2013).

A third strategy for resilience by elevation is to elevate an entire building. This can be accomplished by either using stilts or flotation devices. Buildings within flood hazard areas should be elevated above Design Flood Elevations (DFEs), as determined by FEMA and other agencies (FEMA, 2006). This strategy for elevating buildings will be most cost-effective for new buildings being constructed in flood hazard zones. Retrofitting buildings to be elevated above DFEs may prove to be costly for older buildings, but it is a strategy that could be considered as it will protect buildings from flooding damage within the foreseeable future (Tam, 2009). Examples of elevated buildings can be seen in Marin County, California and New Orleans. In Marin County, buildings have been constructed on poles over salt marshes, with a predictable tidal range. New Orleans now requires new or rehabilitated housing in areas protected by levees to be elevated three feet above DFEs, after the destruction caused by Hurricane Katrina (Tam, 2009). The cost of elevating a building is approximated to be $3 per square foot per foot raised (City of Portsmouth Planning Department, 2013).

Rather than permanently fixing buildings above DFEs, flotation devices can be used to allow buildings to rise during increased water levels. This strategy can be difficult to retrofit on existing buildings, but can be very effective in newly constructed buildings. New buildings designed with flotation devices are very resilient to flooding and are less susceptible to damage from seismic activity (Tam, 2009). Applying flotation devices to buildings is a fairly new technique that has not been thoroughly tested in areas that receive powerful storms. New Orleans has designed new homes that use a specially engineered foundation that allow the home, which is anchored to poles, to float up to heights of 12 ft during times of high sea levels (NBC, 2009). Underneath the homes are air filled cavities that allow them to float on the surface of water. Other cities, including Amsterdam and Dubai, have implemented floating homes on the edge of low-risk water bodies, such as canals and rivers (Tam, 2009). Flotation strategies may prove to be difficult to implement, but could potentially be very effective once more testing has been done.

Living shorelines

Wetlands are living shorelines that have the ability to absorb flood water, as well as minimize erosion time of the coast (Tam, 2009). Advantages include providing habitat for wildlife, filtering pollutants in water, and providing space for human recreation. Disadvantages of living shorelines include the following: they take a long time to develop, take up a lot of space compared to other methods, and require regular management. An example of a living shoreline is the San Francisco Bay area, where numerous sub-tidal eelgrass restorations and oyster reef restorations were implemented (Latta, 2012). The city invested around $100,000 per acre of restoration (Boyer & Wyllie-Echeverria, 2010).

Beach nourishment

Beach nourishment consists of adding a large amount of sand just off the coast so that it is blown and spread by currents to allow the coastline to grow naturally (Tam, 2009). The added sand provides the coastline a bit of cushion against damages due to storms, as well as giving more room for leisurely activities along the beach. The downfall of beach nourishment is that it is a short-term fix to the long-term problem of rising sea levels. The beaches must be properly upheld to provide adequate protection, which can be expensive. A case study was performed on Holland's coast called *The Sand Engine Experiment* to determine how effective beach nourishment is at protecting coastlines from flooding (Slobbe, 2012). This experiment called for providing mega-nourishment for the coastline along the Delfland coast in southern Holland. This artificial coastline, called the Zandmotor, is 100 hectares long and cost 58 million Euros from the national government and 12 million Euros from local cities (Hill, 2013). It was completed in 2012 and the 21.5 million m^3 of sand is expected to take 20 years to distribute (Hill, 2013). So far, it has been found that the experiment will work with the slow and continual changes due to sea level rise, but it will have a harder time protecting against extreme storms (Slobbe, 2012).

Levees, dikes, seawalls, and floodgates

Levees, dikes, seawalls, and floodgates are natural or artificial walls that regulate the levels of water. Currently, Southern Florida contains an ornate system for controlling floods, consisting of canals, dikes, levees, flow control structures, and pumps. The majority of the storm water drainage system is made up of canals (primary, secondary, and tertiary). These are connected to the secondary drainage system of local drainage systems created by the city or county government by other canals (Heimlich, Bloetscher, Meeroff, & Murley, 2009). The canals possess control structures that strategically allow for the withholding and discharge of storm water to the main drainage system, as to not overwhelm the system with too much water all at one time. To maximize the storage capacity of the drainage system, water levels in canals are lowered during times of anticipated water level rises. However, as sea levels rise, there becomes less and less of a difference between water levels on either side of levees, preventing the system from working. Southeast Florida is looking into strategically placing sea gates, implementing high capacity pumps, and redesigning its current system of canals, levees, and flood control structures (Heimlich, Bloetscher, Meeroff, & Murley, 2009). Other examples include:

The Aflsuitdijk dike in North Holland is 32 km in length x 90 m wide x 7.25 m above sea level. It was constructed between 1927 and 1933, made of boulder clay and basalt rocks with two artificial islands with grass offshore. With over 15 million cubic meters of clay and 27 million meters of sand, the dike closed off the Zuiderzee lake from the North Sea, which had caused flooding problems since the 17th century (Hill, 2013).

The Inner Harbor Navigation Canal Surge Barrier east of New Orleans is comprised of a fixed barrier, floodwall, and moveable gates. It is 3,000 meters long and was finished in 2011 after a $1.3 billion investment from Congress. This concrete floodwall with steel reinforcement is expected to reduce the 100-year storm flooding for this region of Louisiana (Hill, 2013).

The Maeslantkering Barrier in Rotterdam, Netherlands is a movable barrier with steel gates that are 22 meters high by 210 meters long. These barriers protect a waterway that is 360 meters wide. This barrier was completed in 1997, costing 250 million Euros. Rotterdam is an important economic center in the Netherlands. The gates close during severe storms to reduce dangerous flooding problems (Hill, 2013).

The Thames Barrier is a moveable barrier that is 520 meters long, protecting 125 km^2 of land in London. It was opened in 1984 and cost over 630 million pounds. It is comprised of 10 steel gates with reinforced concrete piers. The Thames Barrier was first planned after a very destructive flood in 1953 and the current barrier is designed to protect until 2030. London is currently looking toward new designs for construction after 2030 (Hill, 2013).

In Tokyo, there is a super dike that is 14.5 km long x 10 m high x 300 m wide. It was completed in 2009 and cost over $100 billion JPY to construct. Underneath the dike is a tunnel that is 4.5 km long with a diameter of 12.5 m with the ability to hold over 540,000 m^3 of water during flooding. It extends the width of the city and plays a crucial role of reducing flooding in Tokyo (Hill, 2013).

Levees, dikes, seawalls, and floodgates are examples of flood resistance techniques that cities have been using for centuries to protect buildings from flooding. Boston may need to plan for a major strategy like this in the future. For now, buildings can raise the height of seawalls to reduce flooding. The Coastal Resilience Initiative in Portsmouth, New Hampshire estimates that it costs $40 per lineal foot per foot of height of the seawall for residential properties and $90 for business properties (City of Portsmouth Planning Department, 2013).

Appendix B: Memo to the BRA with Adaptation Charts

The Boston Harbor Association
A Voice for the Harbor

To: Chris Busch, Boston Redevelopment Authority
From: Kelly Knopp, Steph Lindow, Kirk Murphy, and Jonah Rosch, Worcester Polytechic Institute
Date: October 17, 2013
Re: Preliminary vulnerability assessment and preparedness options for Boston's downtown waterfront.

Background. Current science predicts that Boston will experience increased sea levels of one to two feet by mid-century and three to six feet by 2100. With the more extreme storm events associated with climate change, waterfront property owners will need to develop both short and long-term preparedness plans to reduce the damage associated with increased coastal flooding.

This memo summarizes research done by a team of Worcester Polytechnic Institution students during fall 2013 to build on findings and recommendations described in *Preparing for the Rising Tide* (The Boston Harbor Association, 2013) and *Building Resilience in Boston* (Boston Green Ribbon Commission, 2013). Specifically, the team used the methods in *Rising Tide* to perform vulnerability assessments for the properties within the boundaries of the Downtown Municipal Harbor Plan not included in *Rising Tide*. The team then used *Building Resilience* and other primary research—including interviewing an expert panel—to develop possible preparedness solutions for individual buildings and at a neighborhood scale.

Methodology. In *Preparing for the Rising Tide*, the Boston Harbor Association conducted risk assessments and sample preparedness plans for the Marriot Long Wharf Hotel, Aquarium MBTA Station, 255 State Street, Harbor Garage and New England Aquarium (the Chart House and Custom House Block declined to participate). These plans are included in Appendix A.

The WPI team used the same methods to prepare sample preparedness plans for the remaining properties in the Downtown Municipal Harbor Plan area: James Hook Lobster Company, Captain John Foster Williams Coast Guard Building, the Rowes Wharf Complex, Harbor Towers, and Christopher Columbus Park. Risk assessments and sample preparedness plans are also included in Appendix A.

Results and Recommendations. Table 1 summarizes relative vulnerabilities among downtown Boston waterfront properties of coastal flooding based on elevation above sea level. "Critical elevation" is defined as the elevation of a vulnerable resource such as a door or vent where salt water flooding would cause damage. Currently, Boston's 100-year flood level is approximately five feet above average (mean) high tide. With expected sea level rise over the next century, we loosely defined properties:

- Within five feet of mean high tide as being at "high" vulnerability,
- Between five and 7.5 feet above mean high tide as being at "moderate" vulnerability,
- Greater than 7.5 feet above mean high tide as being at "low" vulnerability of coastal flooding.

These levels assume no extreme wave action; Boston Harbor is generally well-protected from wind and waves; Please note that the tables in Appendix A use the more precise elevation measure "NAVD" or North American Vertical Datum to measure elevation. NAVD is roughly equivalent to today's mid-tide, but is a measure that will not change as average sea levels rise. Today's mean high tide is equal to NAVD + 4.8 feet.

Table 1. Relative Vulnerability of Downtown Boston Properties to Coastal Flooding

Property	Critical Elevation of Key Resources (in ft NAVD)		
	High Vulnerability	Moderate Vulnerability	Low Vulnerability
Christopher Columbus Park	Seawall-8.357 Electrical box on dock-9.591	Statue-13.800	Trellis walkway-14.587
Marriot Long Wharf Hotel	Below-ground garage-7.5		
Aquarium MBTA Station	Above-ground entrance-7.5		
255 State Street	Street level entrances-9.5		
New England Aquarium		Emergency generators-12	First floor (all electrical equipment and generators are located on the second floor)-15
Harbor Garage	Entrance-9.5		
Harbor Towers	Short seawall-8.22 Opening to air vent-8.711	Outside grate leading to service equipment-11.069 Outdoor electrical outlets on trees-11.235 Main entrance to 85 E. India Row-12.743 Main entrance to 65 E. India Row-11.746	
Rowes Wharf	Seawall-9.752 Ferry terminal door-9.781	Outdoor electrical outlets by docks-13.085 First floor doors-13.131 50 Rowes Wharf main door-13.153 Vent in front of garage (leading to generator)-13.427	Top of dock caps-15.486
Coast Guard Building		Outdoor HVAC and electrical equipment-10.812 Seawall-10.830	First floor-15.063
James Hook Lobster Company			Low risk of flooding throughout property.

Neighborhood-specific strategies. The tables in Appendix A provide building-specific recommendations. As periodic storm flooding becomes chronic tidal flooding over time, neighborhood- or city-wide strategies will be needed to prevent significant damage from salt water flooding. Strategies appropriate for downtown Boston include:

Paired Capacity Investment: This strategy involves pairing the construction of an at- or above-grade structure with below-grade open space connected to the ocean that diverts water away from vulnerable resources in the neighborhood. The BRA might consider incorporating below-grade landscaping as part of the redevelopment of Harbor Garage, James Hook Lobster Company and even possibly Christopher Columbus Park.

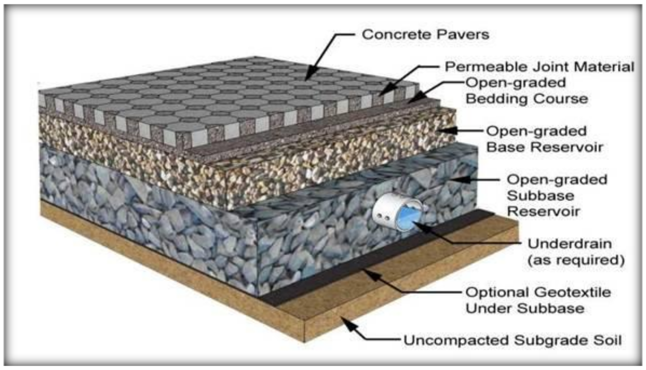
Floodwater is directed to this below-grade public park in Rotterdam, Netherlands to divert the water away from above-grade critical structures.

Below-grade or Underground Water Channels: Similar to a paired capacity strategy for a smaller area, constructing below-grade channels connected to the harbor could prevent more widespread flooding of a larger area.

Over time, as downtown Boston becomes more regularly inundated, turning some side streets into channels with pedestrian access could provide both an aesthetically pleasing urban feature and a means for keeping sea water away from vulnerable resources. This municipal harbor plan should consider which side streets or access points might be most appropriate for future channelization or other below-grade flood control strategies.

The Cheong Gye Cheon Channel in Seoul, South Korea acts as a public recreational area when flooding is not present. During flooding, water is redirected to the channel.

Drainage Systems: We recommend the use of drainage systems such as permeable pavement or French drains to collect water and redirect it to less vulnerable areas (see above).



Permeable pavement can be used as a drainage system and a pathway to redirect water way from vulnerable areas.

Raising and Sloping Roads: Atlantic Avenue could be raised above the 100-year flood zone to remain passable during coastal floods. Sloping roads and sidewalks can redirect water away from buildings toward below-grade channels or drains.

Raised roads are operable during times of flooding and can be used to divert water to below-grade areas.

Conclusion: Implementing building-specific flood control strategies are essential in the short term to prevent damage from extreme storm events. Over time, more substantial changes in infrastructure will be needed to increase the resilience of the downtown waterfront to coastal flooding.

Coastal Climate Change Adaptation Planning	Site-Specific Solutions Christopher Columbus Park
General Description	Boston's first waterfront park is a region with varying elevations. The lowest point includes the seawall along the Harbor, which is 8.4 feet NAVD and at high risk for flooding. The highest point, the trellis walkway, is at an elevation of 14.6 feet NAVD and low risk. This public park space would not receive any extreme flooding until reaching the elevation of the walkway; however, critical equipment is located along the lower elevations of the park, such as electrical boxes and equipment along the seawall at 9.6 feet NAVD, which is high risk for flooding. This requires adaptations in order to protect these key components of the park.

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			
	2050		8.0			
2100			9.0	Flooding by the seawall, sidewalk, and electrical boxes	Raise seawalls, move electrical equipment, add vegetation	$90 per lineal foot per foot of height of seawall
		2010	10.0			
	2100		11.0			
		2050	12.0	Northwest region containing grass areas and open park space begins to experience flooding	Use open space for retention ponds with rain gardens for infiltration, install permeable pavement	Rain gardens $5-$45 per square foot, 2-3 times as much as regular concrete or asphalt for permeable pavement
			13.0			
		2100	14.0			
			15.0	Widespread flooding of entire area, up to the trellis and Christopher Columbus Statue	Lower the drains	To be estimated seperately due to uniqueness of park
			16.0			

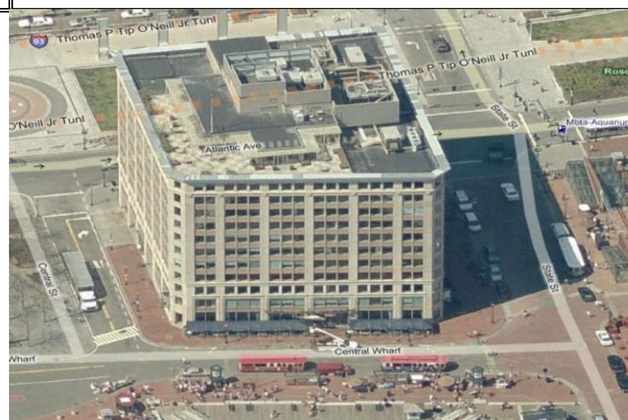
* Initial Capital Costs and Operational and Maintenance costs provided are estimates based on costs from similar types of projects. More detailed and accurate costs would be required for actual engineering and construction.

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*
			4.0	No Flooding Expected	No Action Required	N/A
2010						
			5.0			
2050			6.0			
	2010		7.0			
			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
	2050					
			9.0			
2100				Flooding of Marriott infrastructure and entire Long Wharf region.	See Regional Adaptations	See Regional Adaptations
		2010	10.0			
			11.0			
	2100	2050				
			12.0	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
			13.0			
		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.

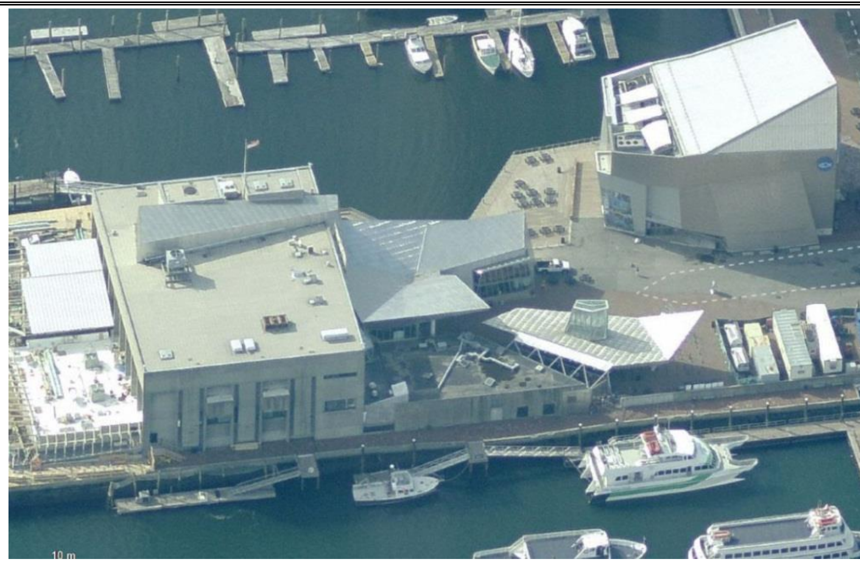
Long and Central Wharves - Coastal Climate Change Adaptation Planning	Two Fifty Five State Street
General Description	The Two-Fifty Five State Street parcel resides landward of Long Wharf. The parcel initially becomes vulnerable at 8.5 ft NAVD, when water floods State and Central Streets around the parcel. 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	No Flooding Expected	No Action Required	N/A
2010						
			5.0			
2050			6.0			
	2010		7.0			
	2050		8.0			
2100			9.0	Flooding of State Street and Central Wharf Street	Dry flood proofing (membrane) on lower levels; or Long Wharf adaptations	*Cost: $5 /ft^2 for waterproof membrane
		2010	10.0			
	2100	2050	11.0	Flooding of Parcel and surrounding areas	See Regional Adaptations	See Regional Adaptations
			12.0	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
			13.0			
		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.

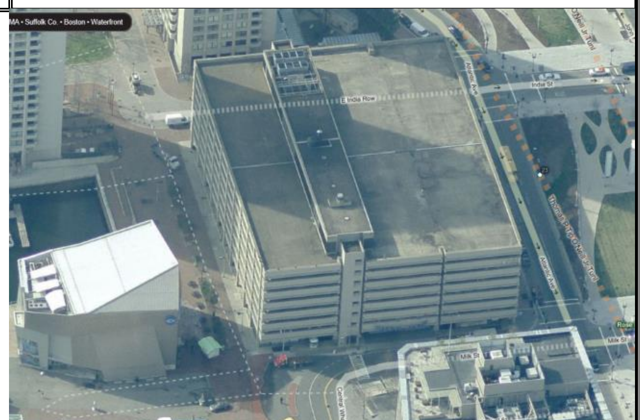
Long and Central Wharves - Coastal Climate Change Adaptation Planning	Site-Specific Solutions New England Aquarium
General Description	Compared to the rest of the region, the New England Aquarium parcel and buildings are less vulnerable to potential flooding due to sea level rise and/or storm surge. 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			
		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
	2100	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.

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)	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					
2100			9.0			
		2010	10.0	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	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.

Coastal Climate Change Adaptation Planning	Site-Specific Solutions: Harbor Towers
General Description	The Harbor Towers are at the highest risk for flooding in the study area. The buildings are already at risk for flooding at the present day's high tide. At height 8 feet NAVD, water will start to reach over the seawalls to flood the air vent opening and is at high risk. The main entrances of 65 and 85 E. India Row will start to experience water at heights 11 and 12 feet NAVD, which are at moderate risk. The water will reach the grates leading to service equipment below at height 11 feet NAVD, which are also moderate risk.

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 (spans ~5.5–6.5)			6.0			
	2010		7.0			
2100 (spans ~7.5–11.5)	2050 (spans ~8–9)		8.0	Minor flooding over north and northeast seawalls	Emergency preparedness and evacuation plan, raise seawalls	$90 per lineal foot per foot of height of seawall
			9.0	Moderate flooding near opening of air vent	Add vegetation, seal basement	$40 per 100 square feet to seal basement
	2100 (spans ~9.5–13.5)	2010	10.0			
		2050 (spans ~11–12)	11.0	Flooding of southeast seawall near the steps, patio wall (corresponding to height of first floor), main entrance to 65 E. India Row, grate leading to service equipment on 65 E. India Row, electrical outlets on trees, main entrance to 85 E. India Row	Relocate/raise HVAC, raise outlets, install French drain, waterproof concrete, use basement as water diversion, permeable pavement	$20 per square foot of building for wet flood proofing, 2-3 times as much as regular asphalt for permeable pavement
			12.0			
		2100 (spans ~12–16)	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.

Coastal Climate Change Adaptation Planning	Site-Specific Solutions Rowes Wharf Complex
General Description	The Rowes Wharf Complex has not experienced much flooding throughout its brief 26 year history. However over the next 100 years, annual 1-year and 100-year storm surges will have a greater impact on the entire complex. For example, the seawall and ferry terminal, both at 9.8 feet NAVD, will be the first areas to be affected by flooding and categorizes these areas to be high risk. Major flooding will occur beginning at the condominium steps at 13.0 feet NAVD, categorizing them as moderate risk. The highest elevation of 15.5 feet NAVD, the dock supports, would mainly be affected during a 100-year storm surge in 2100 and are low risk.

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			
2100	2050		8.0			
2100	2050		9.0			
2100	2100	2010	10.0	Flooding begins to affect ferry terminal and the seawall	Raise seawall and increase vegetation	$90 per lineal foot per foot of height of seawall
2100	2100	2050	11.0			
	2100	2050 / 2100	12.0			
	2100	2100	13.0			
		2100	14.0	Key components of the complex, such as the main entrance and condominium entrances, begin to experience severe flooding	Raise all critical equipment, vacate lowest floor of garage, raise dock posts, move outdoor electrical equipment, cover/divert water from the vent at the garage entrance	$3 per square foot per foot raised for elevating a building
		2100	15.0			
		2100	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.

Coastal Climate Change Adaptation Planning	Site-Specific Solutions Captain John Foster Williams Coast Guard Building
General Description	The Captain John Foster Williams Coast Guard building is at moderate risk for flooding in comparison with the buildings in Rowes Warf and India Warf. The dock begins to flood at 8 feet NAVD at high risk, while the HVAC and electrical systems to the east of the building will be touching water at a height of 10.5 ft NAVD at moderate risk. The first floor is at low risk at 15.1 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			
2100	2050		8.0			
			9.0	Minor flooding on east side of building on the dock	Minor flood proofing, raise the seawall, treat wood with salt water resistant coating	$90 per lineal foot per foot of height of seawall
	2100	2010	10.0			
		2050	11.0	Flooding of east side close to building, water reaching HVAC area outside building	Raise/reclocate HVAC, raise barrier in front of system	N/A
			12.0			
		2100	13.0			
			14.0			
			15.0	Widespread flooding of entire first floor and stairs during storm events	In addition to adaptations above, additional flood proofing and elevation of critical infrastructure, evacuate first floor	$20 per square foot of building for wet flood proofing
			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.

Coastal Climate Change Adaptation Planning	Site-Specific Solutions
	James Hook Lobster
General Description	Compared to the rest of the region, the James Hook Lobster building is less vulnerable to potential flooding due to sea level rise and/or storm surge. For example, James Hook Lobster will not receive critical damage to building until the first floor begins at 16 feet NAVD and at low risk, where the water will reach up to the level of the main door. The base of James Hook is at 12.3 feet NAVD, where the building is at high risk for flooding below the first floor. However, there is no critical equipment until the HVAC system at 19.7 feet NAVD, which is low risk.

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			
	2010		7.0			
			8.0	No Flooding Expected	No Action Required	N/A
	2050					
2100			9.0			
		2010	10.0			
			11.0			
		2050				
	2100		12.0			
			13.0			
		2100	14.0	Minor flooding around base of building, floodwater up to main door at height 16 ft NAVD	Sealants on door and exterior of building, emergency preparedness plan	$40 per 100 square feet to seal basement
			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.

Appendix C: Handouts from Review Panel

October 1, 2013 Review Panel

The Boston Harbor Association

Kelly Knopp, Stephanie Lindow, Kirk Murphy, Jonah Rosch

Contents:

Agenda

Adaptation Sheets

Data Sheets

Agenda for Review Panel
October 1, 2013

Our Project

Objective 1: Vulnerability Assessments
Objective 2: Researching Adaptation Strategies
Objective 3: Finalizing Recommendations for BRA Memo

Our Surveying

- City Benchmark outside of Coast Guard Building with elevation of 13.47 ft NAVD
- Total Surveying equipment
- Errors of closure ranging from 0.014 ft NAVD to 0.071 ft NAVD

Buildings in our study area

- James Hook Lobster Company
- Coast Guard Building
- Rowes Wharf Complex
- Harbor Towers
- Christopher Columbus Park

Included for each building

- Data from our surveying
- Information on building and renovations
- Recommendations for short term and long term adaptation strategies

Neighborhood Strategies

- Retention pond at Christopher Columbus Park
- Raising roads, raising sidewalks, and sloped grade
- Living shorelines
- Beach nourishment
- Levees and dikes

Feedback on our strategies

Other suggestions for improvement

James Hook Lobster Company

- Fire burned down original building in 2008
- Current building is temporary
- Will not be effected until sea levels rise to at least 16 ft NAVD
- Recommended short term strategies:
  - Use sealants and water resistant materials on building
  - Have pumps, sandbags, and flood shields ready for flooding events
  - Prepare emergency supplies and preparedness plans
  - Install French drains leading away from ground floor
- Recommended long term strategies:
  - New building will eventually need to be built with climate change initiatives

Coast Guard Building

- Limited access due to security reasons
- Relatively protected against today's 100-year storm, will need to plan for future sea level rise events
- Recommended short term strategies:
  - Raise seawall in front of HVAC and electrical equipment
- Recommended long term strategies:
  - Move HVAC and electrical equipment to higher grounds
  - Improve drainage systems along dock area to the east of the building

Rowes Wharf Complex

- Joe Gibbons, manager for 15 years
- No major flooding in recent history
- Low lying areas need to prepare for today's 100 year storm
- Replaced docks 8 years ago
- Will be replacing bricks in plaza area in near future
- Garage Floor 5 (G5): 34 ft underground
  - 3000 gal diesel tank for generator
  - Emergency generator for entire complex
- Garage Floor 3 (G3): 15 ft underground
  - Main generator for entire complex
- Garage Floor 1 (G1): 3 ft underground
  - Main electrical switch gear
- Grate in front of garage letting air into generators in garage
  - Unprotected from rain and sea water
- Building has emergency supplies and plans
  - Also has emergency alarms and lights in stair powered by backup generator
- First floor is lobby, offices and residential rooms are higher up
- Recommended short term strategies:
  - Cover grate outside of garage during flooding events
  - Move or raise outdoor electrical outlets
  - Raise seawall in low lying areas
  - Increase vegetation around complex

- Recommended long term strategies:
  - Move critical equipment out of garage
  - Make bottom garage floors into water retention areas
  - Raise dock posts
  - Move grate outside of garage
  - Install permeable pavement during brick renovations leading to city drains and water retention areas

Harbor Towers

- Fran Higgins and Hugh Schaffer, managers for less than a year
- Low lying areas affected by today's 100-year storm
- Most of this area will be affected by 2100's 100-year storm
- Water sitting in basement, visible salt collections and rusting around floor
- Laundry room tiles loose from water intrusion through ground
- Recent $1 million grout injections in walls of basement floor
- Generators and critical equipment in bottom floors
- Severe flooding during New Moon high tide
- Outside air vent leading to generator room leaking
- No emergency plans or supplies
- Garage contains boilers for both Towers
- Recommended short term strategies:
  - Get emergency supplies, prepare emergency plans
  - Get sandbags and flood shields
  - Increase vegetation
  - Raise seawalls
  - Raise or seal vent leading to generator room
  - Move or raise electrical outlets
  - Seal basement
  - Install French drains leading out of basement
  - Waterproof concrete on outside
- Recommended long term strategies:
  - Raise all critical equipment to higher elevations
  - Move grate in front of building
  - Make basement water retention area for buildings

Christopher Columbus Park

- Park and electrical equipment near park could flood in today's 100-year storm
- Statue and trellis walkway elevated protected from sea levels
- Recommended short term strategies:
  - Raise seawalls
  - Lower drains so that they are even with bricks
  - Raise or move electrical equipment outside of Marriott Hotel
- Recommended long term strategies
  - Convert the park into a water retention area
  - Install permeable pavement and use rain gardens to filter water in retention area

Critical Elevations and Potential for Flooding

Measurements taken by Kelly Knopp, Stephanie Lindow, Kirk Murphy, and Jonah Rosch

Table 1 summarizes key ocean level elevations during today's high tide, an annual storm, today's 100-year storm, and Superstorm Sandy in New York City.

Table 1: Reference water elevations

Measurement Reference	Water Elevation
Today's High Tide	4.8 ft NAVD
Annual Storm	7.5 ft NAVD
Today's 100-year storm	9.8 ft NAVD
Superstorm Sandy in New York City	13.5 ft NAVD

*1'-2' projected SLR by 2050
**3'-6' projected SLR by 2100

According to *Preparing for the Rising* Tide, sea levels are projected to rise by one to two feet by 2050, and by three to six feet by 2100. Buildings that are affected by today's high tide or an annual storm are considered at a high risk of flooding and immediate action must be taken. Buildings that could be affected by today's 100-year storm or levels equal to those of New York City during Superstorm Sandy, but not by today's high tide or an annual storm, are at a moderate risk of flooding and action must be taken in the near future. Buildings that are not affected by any of these ocean levels, but will be affected due to projected ocean levels in 2050 and 2100 are at a low risk and action will need to be taken in the future. Table 2 summarizes our definitions for levels of risk.

Table 2: Definitions of risk levels

Water elevation that begins to affect building (ft NAVD)	Risk Level
Below 10	High Risk
10-14	Moderate Risk
Above 14	Low Risk

The critical elevations for each building in our study area and their risk levels are summarized in Tables 3-7.

Table 3: James Hook Lobster Company

Location	Elevation	Risk Level
Bottom of building	12.346 ft NAVD	Moderate Risk
Door/ first floor	16.403 ft NAVD	Low Risk
Window	19.016 ft NAVD	Low Risk
Raised HVAC equipment	19.661 ft NAVD	Low Risk

Table 4: Coast Guard Building

Location	Elevation	Risk Level
Outdoor HVAC and electrical equipment	10.812 ft NAVD	Moderate Risk
Top of harbor seawall	10.830 ft NAVD	Moderate Risk
First Floor	15.063 ft NAVD	Low Risk

Table 5: Rowes Wharf Complex

Location	Elevation	Risk Level
Height of seawall	9.752 ft NAVD	High Risk
Ferry terminal Door	9.781 ft NAVD	High Risk
Top of steps leading to condominiums	13.025 ft NAVD	Moderate Risk
Outdoor electrical outlets by docks	13.085 ft NAVD	Moderate Risk
First floor doors	13.131 ft NAVD	Moderate Risk
50 Rowes Wharf main door	13.153 ft NAVD	Moderate Risk
Vent in front of garage (leading to generator)	13.183 ft NAVD	Moderate Risk
Outdoor electrical outlets on street	13.427 ft NAVD	Moderate Risk
Top of dock caps	15.486 ft NAVD	Low Risk

Table 6: Harbor Towers

Location	Elevation	Risk Level
Height of shorter seawall	8.220 ft NAVD	High Risk
Opening in air vent	8.711 ft NAVD	High Risk
Outside grate leading to service equipment	11.069 ft NAVD	Moderate Risk
Outdoor electrical outlets in front of trees	11.235 ft NAVD	Moderate Risk
Main entrance to 65 E. India Row	11.746 ft NAVD	Moderate Risk
Main entrance to 85 E. India Row	12.743 ft NAVD	Moderate Risk

Table 7: Christopher Columbus Park

Location	Elevation	Risk Level
Height of seawall	8.357 ft NAVD	High Risk
Electrical boxes on dock (outside Marriott Hotel)	9.591 ft NAVD	High Risk
Christopher Columbus statue	13.800 ft NAVD	Moderate Risk
Trellis walkway	14.587 ft NAVD	Low Risk

Appendix D: Summative Team Assessment

While working on our IQP project, we have developed many teamwork skills that have allowed us to work together effectively and respectfully. Flexibility is a skill that our team has developed because there were multiple instances in which circumstances out of our control forced us to change our plans. An example of this was when we were unable to assess the inside of the Coast Guard Building due to security reasons. Rather than leaving this site out of our report, we gathered as much information as possible from the building engineer. We then surveyed important components outside the building such as the HVAC system and the seawall, and we were able to generally assess the vulnerability of the building. Another time that we were flexible was when our sponsor, Julie, wanted us to go to a sustainable economy conference on the same day that our background chapter was due. In order to work with this new plan, we split up, so Kirk and Jonah went to the conference and took notes while Kelly and Stephanie finished the background chapter.

Our team also developed the skill of learning quickly during this project. When were given the surveying equipment, Kirk was the only person with a slight background in surveying. We spent an entire workday of trial and error, figuring out how to use the equipment. We had an error of closure of five inches on our first day, and the following day we were able to attain an error of less than an inch. Another instance in which we learned a new concept quickly was when our advisor, Professor Tuler, suggested that we analyze a second dimension of risk in our vulnerability assessment. Through reading his suggested literature, we were able to include an analysis of the consequences of flooding at each of the five sites within two days.

A third skill that our team has developed over the course of the project is open communication and trust. At the start of the term, we were hesitant to give negative feedback on each other's work. While this method did not create any conflicts between us, it also did not improve our writing. At one point during the term, the team did not feel that Kirk made the edits to his portion of the background chapter to the best of his ability. Kelly, Steph, and Jonah confronted him on this in a constructive way by pointing out where they felt he could improve in his work. He agreed with the suggestions and made the improvements. Using this open communication throughout the term has led to an improved report. It has also built trust between us because we can all rely on one another to give honest feedback.

A skill that we need to improve upon in the future is speaking more equally as a group. Kirk and Jonah are outgoing and Stephanie and Kelly are more introverted. We received comments from our sponsor and advisors throughout the term about how Kirk and Jonah need to hold back and speak less, while Kelly and Stephanie should speak up more frequently. An example of how we have been improving upon this is by having Stephanie lead meetings and giving Kelly the opening slides of the final presentation. Improving these skills will depend on the specific situation that we are in during future group work, but this is something that we will all be mindful of and continue to develop after this term.