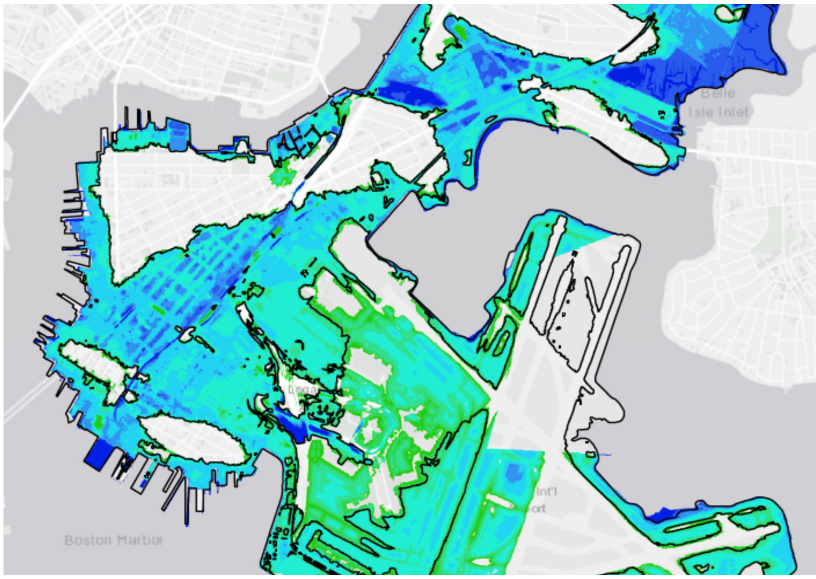
Preparing for the Rise: A Study of Boston's Sea Level and Designs for Coastal Resiliency



A Major Qualifying Project Submitted to the Faculty of Worcester Polytechnic Institute In Partial Fulfillment of the requirements for the Bachelor of Science Degree

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This report represents the work of one or more WPI undergraduate students submitted to the faculty as evidence of completion of a degree requirement. WPI routinely publishes these reports on the web without editorial or peer review.

Abstract

Climate Ready Boston (CRB) began the work of assessing the impact of climate change on the City of Boston in 2016 by looking at the effects of increased temperatures, precipitation, storms, and Sea Level Rise (SLR). The work pertaining to SLR was conducted in anticipation of 36” of SLR by the year 2070. It is expected that new projections set to be released soon will show that Boston will experience 48” of SLR by 2070 instead of 36”. This team was tasked with reassessing the effects of the additional foot of SLR on an area of the City. The team evaluated vulnerable neighborhoods within Boston, and then narrowed the scope of the project to focus on one area that will be impacted by the increase The team created a GIS model reflecting the additional SLR effects in the neighborhood of East Boston, calculated the additional costs associated with the new prediction, and conceptually designed flood barriers to protect vulnerable residents in Boston.

Acknowledgments

The team would like to thank Stantec, and the representatives we worked with on the project: Erica Lotz, Joe Uglevich, Stefani Harrison, and David VanHoven. The team would also like to thank both of our advisors, Professor Albano and Professor LePage, for their support throughout the duration of our work. Lastly, the team would like to extend their thanks to the Stantec employees who lent their time to help the team complete the project: Ben Schattschneider and Jeremy Del Prete.

Authorship

This Major Qualifying Project (MQP) was completed by Civil Engineering and Environmental Engineering Undergraduate Students from Worcester Polytechnic Institute (WPI). All members of the team were responsible for writing, reading, and editing the paper as a whole.

Team member Chase Gaudino was a leader on the stock of East Boston Planned Projects, and the flood protection designs. For the report, Chase wrote parts of the Abstract, Capstone Design Statement, and Professional Licensure. Chase focused on Boston's demographics, CDC Social Vulnerability Index, Social Vulnerability Assessment and its outcomes.

Team member Lauren Kaija was a leader in the creation of the SLR maps at 14' contours and the property damage calculations using the Hazus FAST. For the report, Lauren focused on flood projections and benefit-cost analyses. Lauren wrote sections of the methodology and results related to representation of 48" of SLR in ArcGIS and cost calculations for total structure and content losses. Lauren also looked at other areas of flooding concern in East Boston.

Team member Emilia Perez was a leader on the resident relocation calculations and the alternatives analysis. For the report, Emilia wrote sections focusing on equity in emergency planning, resident relocation and resident relocation costs at 14' contours. Emilia also worked on the different design options for coastal resiliency along with the alternatives analysis.

Team member Hannah Schulz worked with Lauren to assist with the creation of the SLR Maps at 14' Contours, and the Property Damage of Additional SLR. Hannah was a leader for the Additional Business Impacts, and the Flood Protection Designs. Hannah also focused on the community outreach and education parts of the project and will continue to work on those in early 2021.

Team member Trisha Worthington was a leader on the depth grid creation and the social vulnerability assessment. For the report, Trisha wrote parts of the Capstone Design Statement, Executive Summary, and Conclusion. Trisha also worked on the GIS Depth Grid and Shapefile of SLR at 14' Contours, Social Vulnerability Assessment, and Overlay of SVI and Depth Grids maps.

Capstone Design

The Accreditation Board for Engineering and Technology (ABET) requires that all students in an accredited engineering program complete a capstone design experience before acquiring an engineering degree. Through a capstone design experience, students demonstrate skills and knowledge acquired through their studies and coursework. At Worcester Polytechnic Institute, the capstone design experience is fulfilled through the Major Qualifying Project (MQP).

It is predicted that the City of Boston, Massachusetts (the City) will continue to see a rise in sea level in the coming years due to climate change. In 2016, it was predicted that Boston's sea level could rise 36 inches by 2070. Climate Ready Boston created projection maps and sea level rise (SLR) mitigation projects for the original 36 inches for the City to assess how a rise in sea level would impact its residents and infrastructure. However, new predictions show that the SLR could be an additional 12 inches or more, totaling more than 48 inches. To assess the impact of an additional 12-inches of SLR, ArcGIS was used to determine which areas of the City would be proportionally impacted to a more severe extent in 2070 as compared to previous projections. This information was used to determine which social groups and communities would face a greater impact. After taking into account areas with both increased flooding and social implications, a flood protection system was designed for a vulnerable area. This project used civil and environmental engineering principles and addressed the following real-world constraints:

Economic

Climate change increases sea level, storm surges, extreme heat, and riverine flooding events. These events have damage costs. Property damage, resident relocation, and business impacts make up the majority of the total cost of damage due to impacts of climate change events (Sasaki, 2016). Public and private resources will have to pay for damages to buildings, stormwater systems, transportation systems and forced relocation of families and residents. Additionally, as a result of flooding, businesses are repeatedly and frequently interrupted, resulting in a loss of revenue and wages. Property damage and resident relocation costs were calculated for the newly inundated areas in East Boston. Business effects were evaluated by looking at how many buildings would be impacted by the additional foot of SLR. Economic constraints were also incorporated through cost considerations of design options for a flood protection system along Condor Street. Ultimately, the team's updated projection models help identify future inundated areas to inform recommendations of projects that could reduce the costs of the impact SLR will have on Boston.

Environmental

The main focus of the project is to help Stantec and Boston assess how climate change predictions will impact the City and its neighborhoods. Over the past decade there has been a concerted effort to include climate change responses in the master plans for Boston. The City has begun this process in collaboration with Climate Ready Boston (CRB) to prepare for the projected SLR in 2030, 2050, and 2070. The team addressed the environmental impacts of this additional SLR through the application of ArcGIS. The environmental impact of design options for the flood protection system were also considered by the team during the design evaluation process.

Ethical

The project adhered to the American Society of Civil Engineers Code of Ethics. The team was unbiased in decision making for this project and, to the best of their ability, provided a thorough analysis of the impact of SLR and assessed the equitable distribution of Boston's future flood resiliency projects.

Social and Political

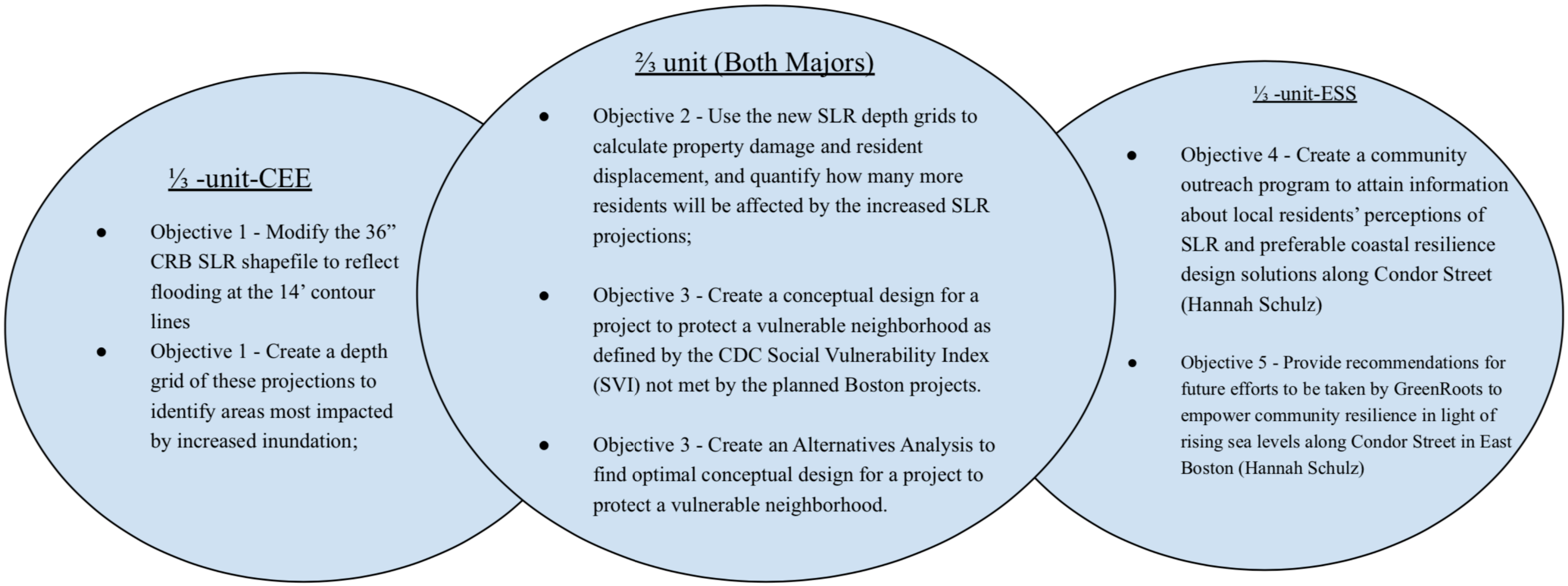
The team compared different social vulnerability layers before analyzing vulnerable groups in Boston to ensure that the data used was comprehensive of as many vulnerable groups as possible. The team decided that the CDC's Social Vulnerability Index (SVI) included more relevant data than CRB's social vulnerability layers and MassGIS's environmental justice layers. The team then overlaid the SVI data to see which vulnerable groups will be located in areas most affected by SLR. This was done to understand the impacts on different social and political demographics. These maps were then compared to the projects planned by Boston to understand where projects might be missing to protect socially vulnerable communities at risk for flooding.

Health & Safety

Safety concerns were addressed in the project by assessing how people will be affected by the rise in sea level. Possible safety concerns include water damage to buildings, damage to materials, and water damage that is exacerbated by freezing. These concerns can lead to structural failure resulting in unsafe conditions in residential and commercial buildings. There are also more immediate public health concerns with flooding, such as basement flooding with combined sewage/stormwater and emergency relocation during a flood event. Depending on the extremity of a flood event, emergency relocation of citizens can be dangerous and present safety risks. While this project did not directly address the impact climate change has on people's mental health, repercussions such as chronic stresses from extreme heat, mental strain from property damage or displacement, and higher levels of stress or anxiety after a disaster was considered throughout the engineering process.

Civil Engineering & Environmental and Sustainability Studies Credit Distribution

Hannah Schulz completed this project as a double-major MQP by distributing credits between both the Civil (CEE) and the Environmental and Sustainability Studies (ESS) 1-unit credits. The additional ⅓ credit was completed in C-term starting in January 2021. Below is a Venn Diagram of the objectives for this project, found in "3.0 Methodology" on page 9, split into respective majors. The objectives presented on the right side of the figure represent those that Hannah completed individually.



Credit Distribution Venn Diagram

Professional Licensure

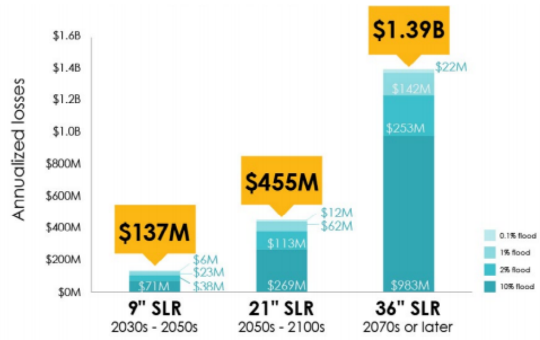
The National Council of Examiners for Engineering and Surveying (NCEES) oversees the Professional Engineering (PE) License to ensure that all engineers are held to a high standard. The PE License helps to safeguard the practice of engineering and ensures that a high standard will be met. There are certain steps an engineer must take in order to obtain a PE license. The first step is obtaining a degree from an ABET-accredited college. Next, it is required to pass the Fundamentals of Engineering (FE) exam to become an Engineer in Training (EIT). After passing the FE exam, the candidate must spend a minimum of four years in the industry learning various practices and gaining experience. The second test is the PE exam, which is administered by each State board, along with a license. After passing the PE exam, the candidate obtains their PE License in that state.

Often, employers prefer students to have taken the FE exam before hiring so that they are on their way to becoming a licensed PE. Engineering plans can only be stamped by licensed engineers which makes them essential to a firm’s work. Obtaining a PE expands opportunities for growth and advancement within the workplace. Additionally, with a PE license an engineer could begin their own private engineering firm. For this project, the team worked closely with professional engineers and project managers from Stantec to help with the completion of the project goals and objectives. This experience allowed the team to gain necessary skills that will help in the next phase of each of the team member’s careers.

Executive Summary

Climate change is already starting to have disastrous effects on our planet. Intense storms are becoming more frequent, coral reefs are dying off because the ocean is becoming more acidic, and the ice sheets are melting (NASA et al., 2020). These repercussions will only become more persistent as the planet's temperature rises. One of the consequences of ocean warming and glacier melting is sea level rise, which was the main focus of this project. Boston, as a coastal city, will continue to experience sea level rise (SLR) which will directly impact its residents and businesses.

Climate Ready Boston (CRB) is an initiative completed by the City of Boston to prepare for the impacts of climate change. In 2016, the CRB team calculated sea level rise predictions for the coming decades and looked at how those numbers would impact residents and businesses during certain flooding events. CRB found that Boston would experience 9" of SLR by 2030, 21" by 2050, and 36" by 2070 based on emission rates at the time. The chart shown lays out the annualized losses associated with each of CRB's SLR scenarios. However, new calculations have been made that show that the SLR by 2070 could be 48" as a result of higher emission rates.



Annualized Losses From Sea Level Rise (CRB, 2016).

The goal of this project, with the support of Stantec Inc., was to ascertain how an additional foot of SLR will impact the residents and businesses in Boston during a 1% annual chance flooding event. To accomplish this goal, the team created three objectives along with two additional objectives to expand upon the community outreach side of the project. The first objective was to modify CRB's 36" SLR with 1% annual chance flooding event shapefile in GIS to represent a 48" SLR scenario. This map was then used to create a depth grid. The second objective was to assess how the new SLR projections would impact property damage, resident relocation costs, and business effects. This was done using the Hazus Flood Assessment Structure Tool (FAST) along with CRB's method of calculating relocation amounts. The third objective was to present coastal resiliency design options for a vulnerable community in Boston. A community in need of a project was determined using the CDC's Social Vulnerability Index, flood maps, and CRB's "future study areas." The design options were determined using an alternatives analysis matrix.

The final two objectives that focus on community engagement were completed by Hannah Schulz in early 2021 (C-term) to satisfy academic requirements for both the Civil Engineering and Environmental and Sustainability Studies degree programs. Hannah's first objective (objective 4) was to create a community outreach program to attain information about local residents' perceptions of SLR and preferred coastal resilience design solutions in the selected area from objective 3. The final objective (objective 5) was to provide recommendations for future efforts to be taken to empower community resilience in light of rising sea levels in the selected area. These final two objectives were assisted by the efforts of the environmental organization GreenRoots.

From objective 1, maps of flooded areas to the 14’ contours were created to represent 48” of SLR with a 1% annual flooding event. These maps are shown in Figures 15-18 in Section 4.1.1. The map of East Boston was then used to create a flood depth grid, which can be found in Figure 19 in Section 4.1.2. In objective 2, the team calculated structure and content losses due to the SLR scenario to be $1.49 billion by 2070. Resident relocation costs were found to be $54.28 million by 2070. Lastly, for business impacts, the team determined that an additional 59 commercial buildings would be affected by the new SLR scenario and 253 commercial buildings would be water locked during a 1% annual flooding event. For the third objective, the team found that Condor Street in East Boston is a vulnerable community that will be impacted by 48” of SLR with no planned projects by CRB. In order to protect this area, the team recommended the implementation of a flood resiliency project. This resiliency project has three design options that when built and deployed together, will provide additional protection during a storm event.

After completing an alternatives analysis, the team found that the best way to protect Condor Street would be to replace the existing sea wall, implement deployable floodwalls at two low points along the coast, and add additional shoreline protections such as a rock revetment and native grasses. Conceptual designs for these recommendations can be found in Section 5.2.2.

Additionally, social recommendations were made for community engagement and community education. Both aspects can be incorporated into the Condor Street flood protection design by adding educational signage along the wall and by adding glass from the nearby beach to the new sea wall as part of a mural. The team also recommends that the City spends more time, money, and resources on educating the community on climate change to ensure residents are informed and are engaged in the flood protection process. Hannah Schulz explored these options more in early 2021 as part of objectives 4 and 5.

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Key Terms and Abbreviations

BCA - Benefit-Cost Analysis
BH-FRM - Boston Harbor Flood Risk Model
BPWD - Boston Public Works Department
BRAG - Boston Research Advisory Group
BSWC - Boston Sewer and Water Commission
CDC - Centers for Disease Control and Prevention
CRB - Climate Ready Boston
DDF - Depth Damage Function
DEM - Digital Elevation Model
DFE - Design Flood Elevation
FAST - Flood Assessment Structure Tool
FEMA - Federal Emergency Management Agency
Gentrification - A process when an increase of residents, typically wealthy ones, and businesses raise property values and can lead to displacement of original residents
GIS - Geographical Information Systems
Hazus - A GIS-based tool developed by FEMA to analyze natural hazards
LiDAR - A method used to measure distances with light emitted from laser pulses
MHI - Median Home Income
NOAA - National Oceanic and Atmospheric Administration
Polygon - A feature type in the form of a shape with three or more sides used to depict spatial data in ArcGIS
QA/QC - Quality Assurance/Quality Control
Raster - A matrix of cells which each represent different values, and can serve as a representation of seemingly continuous data such as air quality, temperature, or satellite imagery in ArcGIS
Sensitivity - The degree to which groups of residents are disproportionately affected by emergency situations and climate change effects
Shapefile - A format used for geospatial vector data storage and organization in ArcGIS
SLR - Sea Level Rise
Social Vulnerability - The susceptibility of social groups to the impacts of hazards such as suffering disproportionate death, injury, loss, or disruption of livelihood; as well as their resiliency, or ability to adequately recover from the impacts (CRB)
USACE - United States Army Corps of Engineers
USGS - United States Geological Survey

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1.0 Introduction

In 2016, the City of Boston launched an initiative called Climate Ready Boston (CRB) to better understand and prepare for the impacts of climate change on the region. Considering that the Organization for Economic Cooperation and Development has ranked Boston as one of the world's most vulnerable coastal cities when it comes to flooding, these actions are especially important (Hallegatte et al., 2013). Preparing and understanding future climate risks can help deter future damages and costs to the City and its people. One outcome of the initiative was a detailed exposure and consequence analysis of the cost to the City of future climate change scenarios. The three climate-related hazards that CRB focused on were chronic stresses of extreme heat, impacts from stormwater flooding, and coastal and riverine flooding events. CRB specifically looked at how 36 inches of SLR by 2070 would affect the City. Since this study, new studies have revealed that SLR could be at least 12 inches higher by 2070 (48") than the 2016 prediction (36").

This project team's goal, with the support of Stantec Inc, was to understand how this updated prediction will affect Boston's residents and businesses during a 1% annual chance flooding event. The team developed three objectives:

- Update the current CRB 1% annual chance flooding event map of 36" SLR to reflect a 48" SLR scenario and create a depth grid of the new projections;
- Assess impacts of SLR on property damage, resident relocation costs, and business effects in the new inundation scenario;
- Provide coastal resiliency design options for a vulnerable community at higher risk of inundation with no current planned project.

The results of this analysis provide Stantec with an updated scenario of inundation conditions within Boston. These new SLR conditions and their impacts can assist in preparation and considerations for the extreme environmental changes that will be seen in the future.

In addition to this goal, to satisfy the academic requirements for both the combined Civil Engineering and Environmental and Sustainability Studies degrees, Hannah Schulz developed a community outreach program to better understand residents' perceptions of SLR and desired amenities of a coastal resilience project for the specified neighborhood within East Boston threatened by erosion from increased precipitation, SLR and tidal surges. The coordination and execution of this program was assisted by GreenRoots, an environmental community-based group in Chelsea, MA.

2.0 Background

The following sections provide the framework on which this project is informed. It is crucial to understand the what and why of a project before developing the how. The group discusses Stantec as a company and how they are connected to CRB, GreenRoots, the history and demographics of the City, how CRB performed the analysis that will be replicated and the consideration of equity in emergency planning.

2.1 Stantec

Stantec Inc. is a design and consulting engineering firm with 22,000 employees and 350 offices worldwide (Stantec, 2020a). The company was started by environmental engineer Dr. Don Stanley in Edmonton, Canada in 1954 (Stantec, 2020b). Sixty-three years later, Stantec was ranked number ten by *Engineering News-Record* on the "Top 150 Global Design Firms" list and number nine on the "Top 300 Architecture Firms" list by Architectural Record (Stantec, 2018). In 2019, Stantec had a revenue of over 926 million dollars. Stantec states that all of their projects are designed with a focus on the community (Stantec, 2020c). Their services include buildings engineering, client enterprise solutions, community development, environment, landscape architecture, sustainability, and water services.

Stantec has worked on projects with SLR and climate change resilience in the past. This work has been done for the Boston Sewer and Water Commission (BSWC) and also in Somerville and Cambridge, Massachusetts. Stantec created models for flood projections in Cambridge (City of Cambridge, February 24, 2020). In Somerville, Stantec contributed to the Climate Change Vulnerability Assessment to help understand how flooding from climate change will impact the City. This assessment, along with outreach and engagement, can be used by Somerville to determine a plan to mitigate those actions (Stantec, 2017).

2.2 GreenRoots

GreenRoots is an environmental protection organization based out of Chelsea, MA that has served the community for more than 25 years. Working across neighborhoods, GreenRoots' goal is to actively pursue greater quality of life and environmental justice through unity, education, youth leadership and collective action. Within East Boston, GreenRoots developed a Chelsea Creek Community Vision plan in 2002 to rethink the opportunities of the waterfront along Chelsea Creek. One of the current environmental justice concerns of GreenRoots is a stretch of land that is experiencing coastal erosion near a residential area in East Boston. The team came across this potential design location during the GIS/SVI mapping process and a need for a future project was later determined after assessing the future planned coastal resiliency projects for East Boston.

2.3 History of Boston's Development

The landscape of Boston was forever changed during the Industrial Revolution when hills were excavated and used to fill in the bay area. During the 17th century, Boston nearly doubled in size due to these infills, as seen in Figure 1 (Whitehill, 2000). Boston has been traditionally protected from storm surges and waves by the Harbor Islands, which have created a false sense of security (Sasaki, 2016). The City was built only a few feet above the water. Thus, today the City experiences high tides known as “king tides.” Boston has also been recently impacted by various storm surges such as Hurricane Sandy in 2012 and Winter Storm Grayson in 2018, which caused the high tide to hit 15.1 ft, a similar record to the Great Hurricane of 1938 (Boston Discovery, 2020). Climate change has started the return of Boston’s coastline to its pre-industrial landscape with SLR. In other words, sea level elevation is starting to negate the raised elevation the infills provided. Storms are also becoming more frequent and more destructive due to climate change (Climate Ready Boston, 2016).

It is also important to note that Boston’s drainage infrastructure is composed of 670 miles of storm drain and 155 miles of combined sewer lines (BWSC, 2020). While the City is in the process of separating sewer from stormwater in certain areas of combined collection, the existing systems can overflow in extreme storm events, causing small amounts of waste to be mixed with stormwater flow. The extent of risk to public health caused by these events is uncertain; regardless, sewage overflow is displeasing for communities to live with and puts the public and the environment in danger of exposure to sewage during flooding (EPA, 2004).

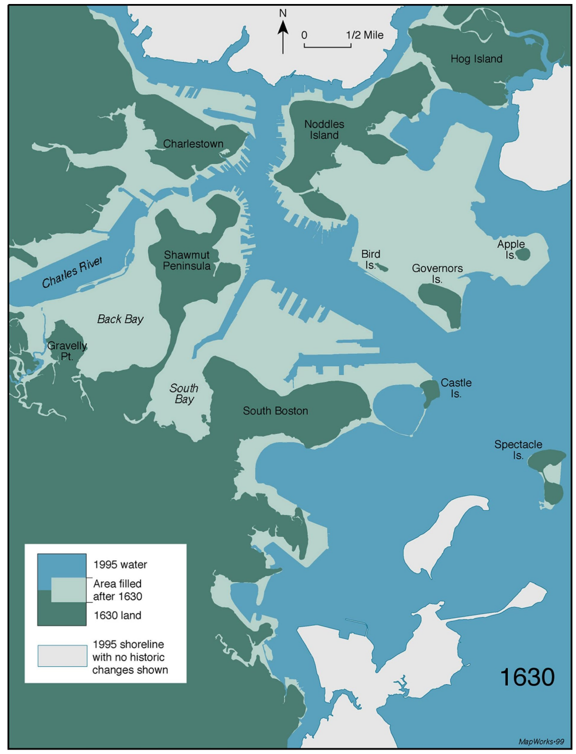

Figure 1. Historical Infill of the City of Boston

2.4 City of Boston Demographics

The following data on the City of Boston was taken from the U.S. Census Bureau (United States Census Bureau, 2019). For reference of Boston’s demographics as a city, 11.2% of Boston’s residents are 65 and over, 16.2% are under 18 years of age. 28.5% of residents are foreign born. Foreign-born persons include anyone who was not a U.S. citizen or a U.S. national at birth, however the data also encompasses respondents who are a U.S. citizen by naturalization or who are not currently a U.S. citizen. The Hispanic or Latino community is composed of 12.5% of Boston’s residents, and 16.1% are Black or African American. For residents of ages 5 and older, 38% of the city speaks a different language than English at home. Race and Hispanic Origin data is based on self-identification. Self-identifiers for race generally reflect a social definition recognized in the country, and not an attempt to define race for any other reason including biologically or genetically. 8.6% of residents under the age of 65 are persons with a disability and 4.2% of residents are without health insurance and under the age of 65. The Census Bureau and American Community Survey include a variety of characteristics to define ‘disability’. These characteristics include hearing, vision, cognition, ambulation, self-care, and independent living. Activities like bathing, dressing, ability to run errands such as shopping were also taken into consideration. Additionally, 20.2% of Boston is considered to be in poverty. For persons in poverty, the Census Bureau uses a set income baseline that varies with family size to determine who is in poverty. If the family's total income is less than the family's baseline, then that entire family is considered in poverty. The official poverty definition does not include the use of non-cash benefits such as Medicaid, public housing, and food stamps.

2.5 Climate Ready Boston

CRB is an "initiative to get the City ready for the long-term impacts of climate change" (Climate Ready Boston, 2016). The project was started in November 2015, and CRB's official report was released on December 6, 2016. There are four sections of CRB: Updated climate projections, vulnerability assessments of climate change hazards, focus areas, and climate resilience initiatives. Climate scientists from the University of Massachusetts Boston, known as the Boston Research Advisory Group (BRAG), developed the climate change projections. CRB's updated climate projections incorporate three different hazards of climate change: extreme temperatures, storm water flooding, and coastal and riverine flooding. The City of Boston recognizes the importance of preparing for the effects of climate change and appointed CRB to identify the associated costs. To evaluate the cost of climate change to the City, the project considered the cost of infrastructure damage, property damage, resident displacement, business disruption, and more. After calculating the cost of damages throughout the City, CRB identified key climate resiliency initiatives that would help prevent or mitigate this damage. Some of these projects involve educating residents on the impact of climate change and how they can help slow the effects by changing some of their own habits, adapting buildings, and improving infrastructure.

Major findings from the 2016 CRB report indicate that by the late century, even without storm surges, 5% of the City will be flooded. Without any projects that prevent damage caused by sea level rise, by 2030s-2050s flooding from 1% annual chance storms will cost $2.3 billion in damages. These events will flood 2,100 buildings, impacting 1,600 residents. That number is expected to rise to 11,000 structures and 85,000 residents by the 2070s. An important takeaway of CRB is the compounding threat of flooding and storm surges in the future. An annual 1% probability flood event in 2030-2050 will become a monthly flooding event in 2070 (Climate Ready Boston, 2016). CRB wrote a supplementary appendix detailing how these calculations and analyses were obtained, both through spatial analysis software and the Federal Emergency Management Agency (FEMA) flood-model estimation methodologies.

CRB provided spatial maps of several socially vulnerable groups: older adults, children, people of color, people with limited English proficiency, people with low-to-no-income, people with medical illnesses and cases of medical illnesses. However, other than an infographic outlining census areas of low to no income households that will be impacted by 36" of SLR, there was no explicit strategy outlined to prioritize projects for socially equitable resilience. CRB's Strategy 5, found in the Climate Resiliency Initiatives describes Initiative 5-2 of Creating a Coastal Protection System as determining a consistent evaluation framework for flood protection prioritization. The report says: "It is critical to consistently quantify the social, environmental, and economic benefits of each alternative intervention—with particular attention to social equity and the needs of socially vulnerable populations—so that they can be weighed both against the costs of the project and against each other. Any evaluation framework must compare a baseline "without project" scenario, in which flood risk continues to increase with SLR, to "with project" scenarios, in which flood risk is managed through appropriate interventions" (Climate Ready Boston, 2016).

2.6 Flood Projections and Benefit-Cost Analysis

CRB used the Boston Harbor Flood Risk Model (BH-FRM) in accordance with Geographic Information Systems (GIS) software called ArcGIS by Esri to perform exposure and consequence analyses for twelve different inundation scenarios. Developed by the Massachusetts Department of Transportation (MassDOT), the BH-FRM is a complex hydrodynamic modeling system that incorporates mathematical representations of the flow patterns of water under different scenarios. The tool is not available for public use, but details as to the science supporting its calculations are recorded in a 2015 report by MassDOT and the Federal Highway Administration (FHWA).

GIS is a powerful tool used for spatial analysis of both geographic and social/demographic data originating from many different sources. GIS makes it possible to recognize new relationships and characteristics between combined datasets, which in turn strengthens new predictions and decisions.

In order to understand the impact of a certain flooding scenario, CRB manipulated data through overlay and analysis tools detailed in their report (Figure 2). By pulling data from reputable sources like MassGIS, Boston Open Data, and MassDOT among others, CRB aggregated and cross-checked data to create an accurate replication of the City of Boston's infrastructure and demographics. They modeled and analyzed three sea level rise (SLR) scenarios: 9", 21", and 36", with each divided further into four different coastal flooding scenarios: 10%, 2%, 1%, and 0.1% annual chance events (also commonly known as, respectively: 10-year, 50-year, 100-year, and 1,000-year floods). Accounting for stormwater flooding with a ten-year, 24-hour rain event defined by the Boston Sewer & Water Commission, the analysis totaled twelve flood scenarios including both coastal and riverine flooding. After completing data aggregation and manipulation, CRB was able to further assess inundation impacts at infrastructural and social levels. They used FEMA's Multi-Hazard Loss Estimation Methodology manual, deriving specific damage and relocation costs/loss estimates from parameters outlined by FEMA through extensive national datasets and technologies.

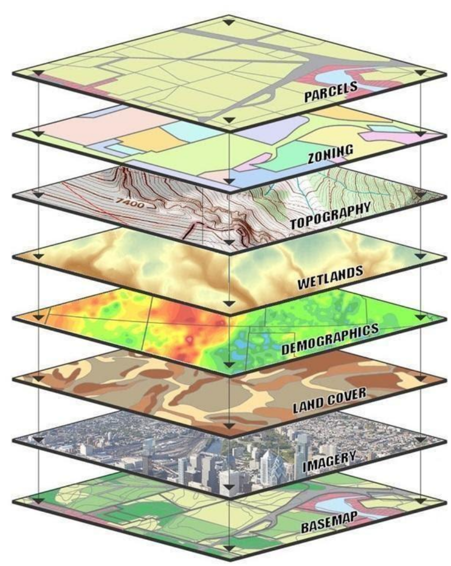

Figure 2. CRB's Layers of Data Used for Analysis (Ontario County, NY. 2016.)

Climate projections since the release of the 2016 CRB report have predicted a greater SLR by 2070 of 48" or more as opposed to the previous 36" SLR prediction. This is a result of more extreme climate change models: assumptions and projections are now higher due to human activity. SLR and subsequent storm surges are anticipated to have larger impacts on infrastructure, businesses, and residents than the initial exposure and consequence analysis.

The focus areas CRB defined in their report are Charlestown, Charles River, Dorchester, Downtown, East Boston, Roxbury, South Boston, and South End. The vulnerability assessment CRB completed concludes that there are four concentrated areas of the City that will be impacted more severely than others by inundation in the near future. These neighborhoods of major concern are South Boston, Downtown, East Boston, and Charlestown. When the report was released in 2016, planning initiatives for climate resiliency were first focused on Charlestown and East Boston. The South End is also a concern, but not until later in the century. Areas such as the Seaport and East Boston have been recently developed and are also under threat of inundation. This recent investment presents an opportunity to leverage action from developers for the resiliency of these areas.

The threat of inundation also presents a unique opportunity to design infrastructure that prevents damages due to SLR while simultaneously improving the City's amenities. This is commonly described as a project's "additionality." While gray infrastructure such as floodwalls present short-term prevention of damage, these solutions can be costly due to their limited functionality. Projects like levees, designed to be recreational trails and parks, that also function as hold space for water, take an innovative approach increasing the benefit of the project for the City.

2.7 CDC Social Vulnerability Index

It is important to consider socially vulnerable populations when assessing the future impact of climate change on the City of Boston. The CDC SVI uses Census data and ranks "each tract on 15 social factors including poverty, lack of vehicle access, and crowded housing" (*CDC SVI Fact Sheet*, 2019). The 15 factors can be seen in Figure 3 and are mapped into four themes: Socioeconomic Status, Household Composition, Race/Ethnicity/Language, and Housing/Transportation. The SVI is calculated and displayed for each census tract. The index is a percentile ranking value from 0 to 1 that can be adjusted to compare vulnerability of census tracts on a federal level and on a state level. Higher values indicate higher relative vulnerability. When viewing SVI data, the percentile ranking can be viewed with sole consideration of the individual social factor, a specific vulnerability theme, or all four vulnerability themes summed together. For an SVI that only considers the individual social factor, the percentile rankings of the individual social factor of interest for each census tract were used to calculate the SVI. To determine the percentile ranking for each of the four themes, the percentiles of the variables compromising each theme were summed and ordered. For the overall SVI, the sums of all four themes were totaled together, census tracts were ordered, and then overall percentile rankings were calculated.

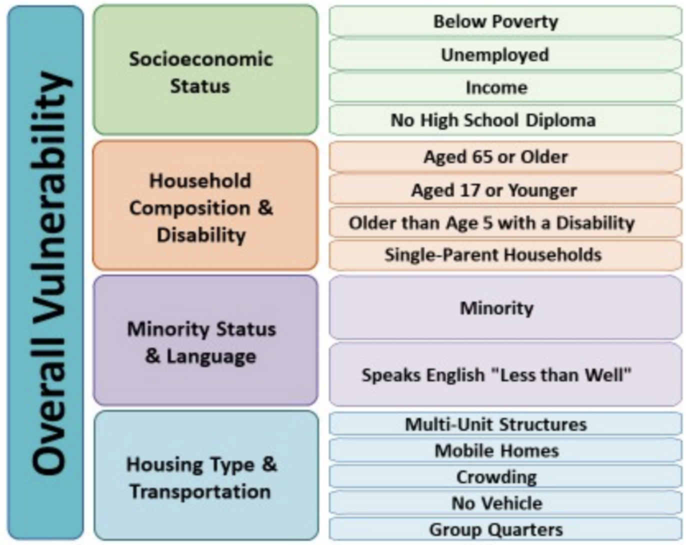

Figure 3. Vulnerability Social Factors that Compromise the 4 Themes for SVI

2.8 Equity in Emergency Planning

Studies from around the world repeatedly demonstrate that minorities are disproportionately affected by climate change. People of color, people with low income, and other minorities tend to live in areas with less elevation and with poorer quality housing. As a result, these people are affected more by the damages and repercussions of coastal flooding and storm surges. Not only are the effects of flooding and storm surge events felt more by low-income and minority people, but they are also likely to happen more often and severely in densely populated, low-lying urban areas commonly composed of vulnerable communities. These areas tend to also have less green space to absorb runoff (Reckien et al., 2017).

Increasing SLR poses significant threats for public health and socially vulnerable groups which are identified by many factors such as age, income, racial distribution, access to transportation, homelessness, disabilities, and language barriers. In emergency situations, it is important to consider how these vulnerabilities impact a community. Older residents are more likely to have preexisting health conditions or develop health problems over time. As mentioned above, income can play a large role in emergency situations. Similarly, persons who are homeless may have a harder time relocating. Mobility and the ability to relocate quickly is an important factor to consider with emergency planning. Persons with disabilities or medical illnesses may have a harder time, and the cost of displacement can be very expensive if persons need additional support. Additionally, in Massachusetts, the city with the highest immigrant population is Boston, making it home to many different languages (*New Bostonians Demographic Report*, 2005). Emergency announcements are not as accessible to those whose first language is not English. A final social vulnerability the team looked at is racial and minority distribution. Historically, minority communities have lower incomes and less wealth which makes financial recovery from the effects of climate change more difficult. For example, people with lower income often have most of their wealth embedded in their property, while individuals with high income have a wider array of assets, as shown in Figure 4. This makes recovery from a total loss of property damage in a flood significantly harder for someone who does not have the financial resources to replace their belongings (Reckien et al., 2017). Further, even the cost of temporary displacement due to unsafe conditions as part of a flood has a significantly higher impact on a person with low income.

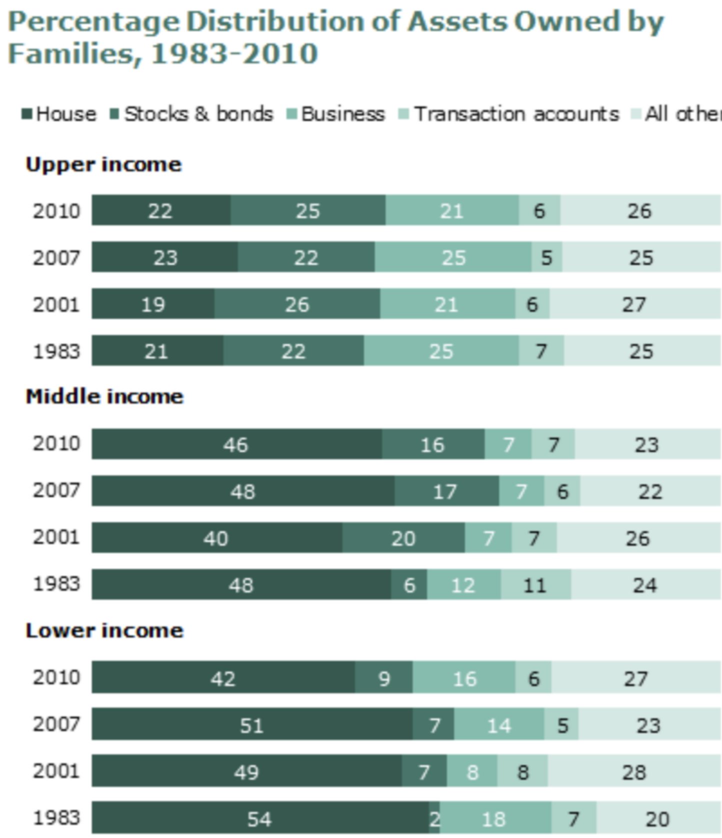

Figure 4. Composition of Assets (Chapter 7: Income and Wealth, 2012)

Several cities throughout the United States are beginning to consider equity in planning for climate change and its associated disaster events. Many attribute the shift to equity-based planning to the FEMA response to Hurricane Katrina's effects on New Orleans. Large neighborhoods in New Orleans are home to many minority and low-income groups. These people were not prepared for the storm and lacked access to funds and resources to relocate and eventually rebuild afterwards (Pierre & Stephenson, 2008). Some cities, like Portland, Oregon, have created an Office of Equity and Human Rights to “promote equity and reduce disparities based on race and disability within city government as its primary task” (Portland Office of Equity and Human Rights, 2020). Massachusetts has implemented a Municipal Vulnerability Preparedness Program (MVP) that helps towns plan for climate change and encourages consideration of social issues through the process (Municipal Vulnerability Program, 2020). It is essential to dive deeper into the social and economic aspects of climate change as the City of Boston works to prepare for its effects. Considering social and economic factors in this planning allows the City to better protect its most vulnerable populations that often feel the effects of climate change more acutely than others.

3.0 Methodology

The goal of this project was to assist Stantec and the City of Boston with an assessment of how new climate change predictions will impact the City and its respective neighborhoods. After creating the flood maps to represent the 48" SLR, time and resource constraints led the team to focus its work on the neighborhood of East Boston for the rest of the project. East Boston was chosen because it was identified by CRB as one of the two neighborhoods with the highest percentage of potential residential damage and exhibited significant levels of social vulnerability. For the final design component, the team focused on a neighborhood in East Boston at risk for significant inundation due to a crumbling retention wall. The team developed three objectives that were used to help meet this goal:

- Objective 1 - Modify the 36" CRB SLR shapefile to reflect flooding at the 14' contour lines and create a depth grid of these projections to identify areas most impacted by increased inundation;
- Objective 2 - Use the new SLR depth grids to calculate property damage and resident displacement, and quantify the number of businesses newly affected;
- Objective 3 - Create a conceptual design for a project to protect a vulnerable neighborhood as defined by the CDC Social Vulnerability Index (SVI) not met by the planned Boston projects.

Following the completion of this report, Hannah Schulz completed the next objectives to fulfill the requirements for a combined Civil Engineering and Environmental and Sustainability Studies MQP:

- Objective 4 - Create a community outreach program to attain information about local residents' perceptions of SLR and preferable coastal resilience design solutions along Condor Street
- Objective 5 - Provide recommendations for future efforts to be taken by GreenRoots to empower community resilience in light of rising sea levels along Condor Street in East Boston

The following sections describe the methods that the team used to meet the goal and objectives.

3.1 GIS Shapefile & Depth Grid of SLR at 14' Contours

Maps representing 48" SLR were created for every coastal neighborhood in Boston. These maps were evaluated for additional flooding impact, and in conjunction with the CDC's SVI, East Boston was chosen as a focus neighborhood. For this reason, a raster illustrating flood depths (a depth grid) at every inundation area was created for only East Boston.

3.1.1 GIS Shapefile of SLR at 14' Contours

Assessing how an additional foot of SLR will impact Boston required collecting numerous datasets, shapefiles, and rasters in order to perform overlays and analyses in ArcGIS. The team used the CRB Approach and Methodology Appendix as a reference for which data sources should be incorporated and how the data was manipulated. Time and manpower constraints prevented a thorough quality assurance and quality control (QA/QC) like CRB's. For example, CRB combined sets of similar data from multiple sources (i.e. building footprints compiled by MassGIS, the City of Boston, and Boston's Impact Advisory Group) to create one master set of data to be as accurate as possible. For this project, the team referenced a few sources for each type of data such as MassGIS, BostonMaps, Analyze Boston, or MassDOT. Similar data layers between the sources were compared, and the most accurate layer was chosen based on the goals of the project. For example, LiDAR digital elevation models (DEMs) from the National Oceanic and Atmospheric Administration (NOAA), United States Geological Survey (USGS), and MassGIS were collected and evaluated. A DEM is produced by measuring wavelengths of light to produce a 3D representation of a certain area of terrain. The NOAA DEMs proved to be the most compatible with the level of precision and units needed to effectively redefine the CRB flood layer. A table of each data set used for this analysis can be found in below in Table 1.

Table 1. Relevant GIS Layers

Dataset	Source
CRB - SLR Inundation (9", 21", 36")	OpenData
CRB - Coastal resilience Project Tracker	BostonGIS
Ortho Imagery	MassGIS OLIVER
LiDAR - NOAA DEMs	NOAA Data Viewer
Contours - 1ft	NOAA DEM
Boston Neighborhoods	OpenData
Boston Buildings	OpenData
Buildings	BostonGIS
Parcels 2016 Data Full	Assessor Data
Parcels 2020	Assessor Data
CDC Social Vulnerability Index (SVI)	Agency for Toxic Substances and Disease Registry

The team modified CRB's layer titled "36inch Sea Level Rise 1pct Annual Flood," from Analyze Boston to create a polygon to represent 48" SLR. The reason this particular flood event was chosen is because the greatest amount of flood damage is caused from 1% chance storms and no public layer is available for 0.1% chance flooding.

Contour polygons at 1' intervals were created out of the LiDAR DEMs from NOAA using the "Contour" Spatial Analyst tool in ArcGIS. The 36" CRB flood layer was overlaid with these contours, which revealed that the flood layer roughly followed the contours at 13' of elevation.

Using the bathtub approach, the team expanded CRB's 36" flood layer to encompass all hydrologically connected areas at or below the 14' contours by using the "Selection by X" and

"Merge" tools in ArcGIS. The 14' contours were the best option for modeling SLR at 48" as accurately as possible while still allowing for the simplified bathtub approach.

3.1.2 GIS Depth Grid of SLR at 14' Contours

After modeling the inundation along the 14' contours, a flood depth grid was created of the inundation areas. This was done in ArcGIS by clipping USGS LiDAR data to the area of East Boston that would be flooded. This isolated elevation data of East Boston's flooded area in raster form.

The raster was then duplicated, and the copy was set to an elevation of 14'. Outliers from the East Boston elevation raster were removed using the "Raster Calculator." This was done to make calculations simpler by setting all negative numbers to zero. Additionally, elevations above 14' were set to 14'. Finally, the Raster Calculator was used to create the flood depth raster by subtracting the 14' elevation raster from the East Boston elevation raster. A diagram of this process is depicted in Figure 5. The same process using 13' contours was used for CRB's 36" flood layer to create a depth grid for the 36" SLR scenario to compare to the 14' contours depth grid. See section "3.2.1 Property Damage Using the Hazus Fast tool" for how the 14' contours depth grid was used to complete the property damage calculations.

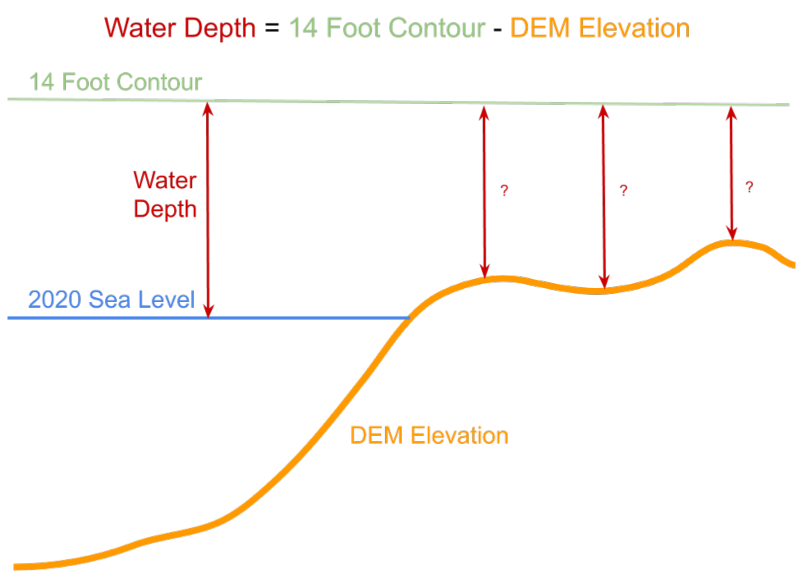

Figure 5. Diagram of how water depth was calculated

3.2 Impact Assessment

After the team created new GIS layers with SLR extended to 14' contours, areas that experienced greater flooding were pinpointed. When calculating overall flood costs, impacts from SLR, storm surges, and riverine flooding events are usually included; however, for this MQP, the team only focused on structural/contents damage and relocation costs from SLR.

3.2.1 Property Damage Using the Hazus FAST tool

Structural and contents damage costs were calculated using the Hazus Flood Assessment Structure Tool (FAST). Before calculating the costs for the 14' contours, costs were calculated for the 36" SLR with 1% annual chance of flooding in East Boston. Performing a cost analysis for the 36” SLR enabled the team to compare values from this tool with CRB’s results in order to make an assessment as to the significance of the differences.

An Excel spreadsheet was used to compile the data necessary for the completion of this calculation. This included building occupancy classes, building cost, building area, number of stories, foundation type, first floor height, content cost, and latitude and longitude data. The depth grid created in the previous objective was used in conjunction with the Excel sheet containing spatial and attribute data. In Figure 6 is a screenshot of the files used and the FAST input fields required in the user-defined data.

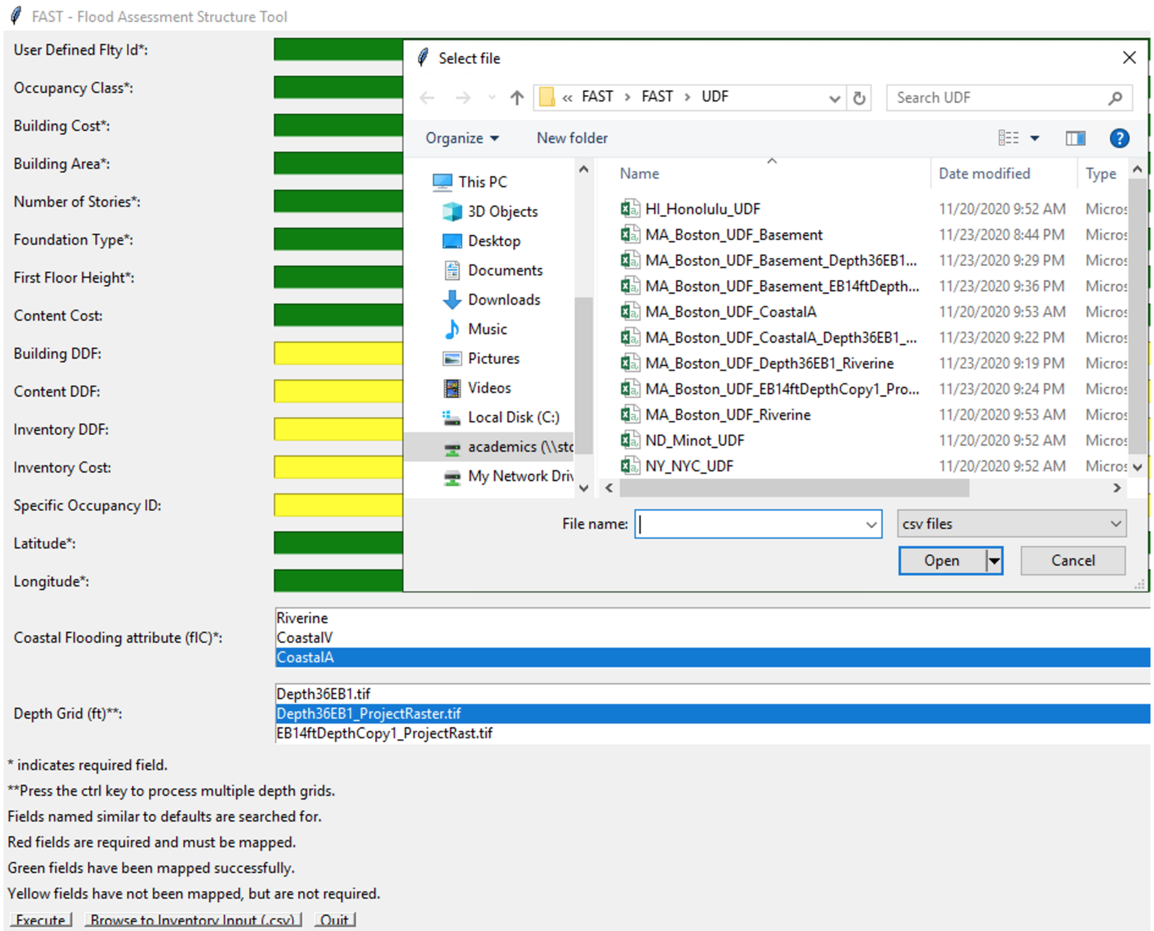

Figure 6. Screenshot of the FAST program input fields and files

The FAST tool requires a specific cell format for each column of data, as well as a specific format for the depth grid input. The 36” SLR and 14ft Contour SLR depth grids were reprojected to a compatible coordinate system (WGS 1984) and converted to TIFF files. On the left-hand side of Figure 6 is a list of the required data fields. Fields in yellow are optional and automatically populated with default values if not provided by the user. Boston building data was obtained from multiple sources for cross-checking purposes and completeness. A complete list of the layers and tables used are provided in Table 1.

Property damage costs of the East Boston inundation areas were determined using building replacement values (BRVs) and contents replacement values (CRVs) calculated by

CRB (Figure 7 is an abbreviated version of the CRB Replacement Values, the full table can be found in Appendix B) based on:

- FEMA's Multi-Hazard Loss Estimation Methodology (Hazus)
- RSMeans Building Construction Cost Data
- US Army Corps of Engineers (USACE) Studies

Hazus	Occupancy Code	BRV	CSRV	CRV
RES1	Single Family Dwelling	$143.14	0.69	$98.77
RES2	Mobile Home	$137.47	1.14	$156.71
RES3A	Multi Family Dwelling - Duplex	$117.76	0.69	$81.25
RES3B	Multi Family Dwelling – 3-4 Units	$227.31	0.69	$156.85
RES3C	Multi Family Dwelling – 5-9 Units	$227.31	0.69	$156.85
RES3D	Multi Family Dwelling – 10-19 Units	$216.42	0.69	$149.33

Figure 7. CRB Replacement Values (Climate Ready Boston, 2016)

Starting at the top of the figure, "User Defined Flty Id" is a facility identification number assigned by the user and has no numeric importance to calculations. "Occupancy class" is defined by the Hazus Codes in Figure 7 matched up with respective BRV and CRVs. Occupancy information was only available in the form of PTYPES, or property occupancy codes for the City of Boston. The PTYPES attributed to the buildings in East Boston were matched up either automatically with the corresponding Hazus code, or on a case-by-case basis in the event that a Boston occupancy code was not directly comparable to a Hazus code. For example, PTYPEs 130, 131, and 132 all stand for "Vacant Land", which is not taken into account in Hazus FAST calculations. These properties, however, might now contain a building that did not exist when the data was recorded. Older datasets with attributes such as "Style" and "LU" (Land Use), as well as Google Maps Streetview were used to confirm the existence or absence of buildings and accurately assign Hazus codes. A full list of the Hazus codes used for each PTYPE is in Appendix C.

"Building Cost" and "Content Cost" were both calculated by multiplying the BRV and CRV values in Figure 7 by the "Building Area" to obtain total building and content replacement costs for each property. Area of buildings was provided by the 2019 Boston Assessor's data; however, many area values from this data remained zero which meant they were excluded from any cost calculations. "Number of Stories" was also provided in this dataset.

"Foundation Type" is an attribute that was not provided in any datasets the team found, so further research allowed the team to make educated assumptions. In the initial expansion of the city, when mud flats were filled, wood pilings were also inserted to provide extra support to buildings. As seen in Figure 8, the default first floor elevation (which is not elevation above sea level, but elevation above ground) for a pile foundation is 7 or 8ft (depending on construction before/after 1974). These settings "exist" but are "typically not allowed"; the default foundation type and corresponding first floor elevation if user-defined data does not exist is "Slab" at 1ft. During the team's site visit, however, basements were identified in many residential buildings in East Boston, so this was also a feasible setting for running the cost analysis.

Table 1-1: Default Floor Heights above Grade to Top of Finished Floor (Riverine)

ID	Foundation Type	Pre-FIRM	Post-FIRM
1	Pile	7 ft.	8 ft.
2	Pier (or post and beam)	5 ft.	6 ft.
3	Solid Wall	7 ft.	8 ft.
4	Basement (or Garden Level)	4 ft.	4 ft1
5	Crawlspace	3 ft.	4 ft.
6	Fill	2 ft.	2 ft.
7	Slab	1 ft.	1 ft1

Source Data: Expert Opinion Note: 1 is typically not allowed, but may exist

Figure 8. Default Hazus First Floor Elevations based on Foundation Type (Cutrell et al., 2018)

Building and content DDFs, or Depth-Damage Functions, are automatically populated by the FAST tool based on all other given information, if not user-defined. A DDF curve illustrates the relationship between depth, duration, and type of flooding to the percent of expected damage to a structure and its contents in a flood event. DDFs have been developed through comprehensive flood studies by USACE and other professional organizations. An example of one is in Figure 9. Latitude and longitude values were obtained from spatial buildings data.

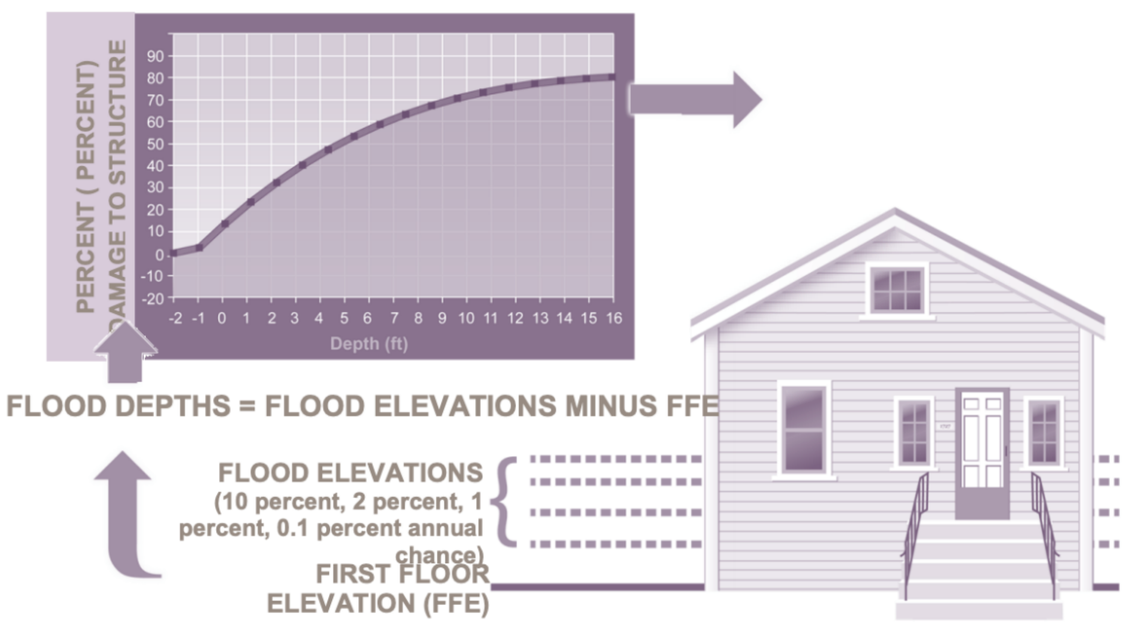

Figure 9. Depth Damage Curve Explanation (Climate Ready Boston, 2017)

Finally, the “Coastal Flooding attribute” was set to CoastalA. This is described by FEMA as the area landward of a V zone (see Figure 10), and experiences flooding as a result of storm surges and wave action as opposed to riverine flooding.

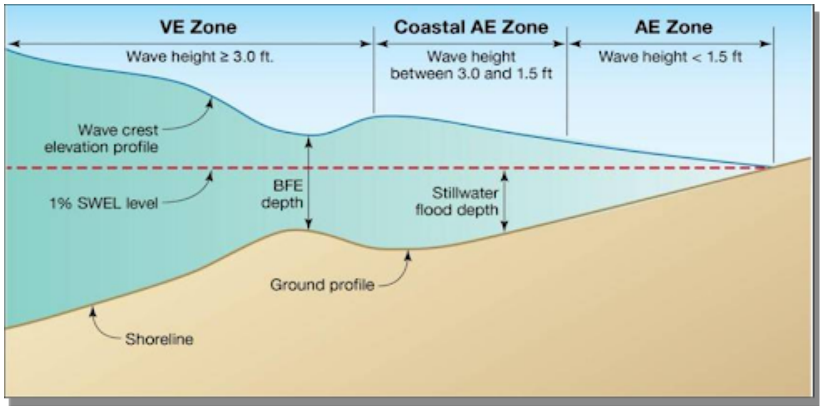

Figure 10. FEMA's CoastalV and CoastalA Zones for flooding (FEMA, n.d.)

After aggregating and populating all necessary fields, a number of scenarios were run using the 36" SLR depth grid to determine which scenario most closely represented the values from CRB's impact assessment. Once the most accurate scenario was identified, the same values could be used along with the 48" SLR depth grid to obtain a value for total structure and content loss in a 1% chance storm event with 48" of SLR.

3.2.2 Resident Relocation

Resident relocation costs were calculated using similar sources and approaches as the CRB methodology. The information and the equation in Figure 11 outline the relationships and values needed to complete this cost analysis.

$$\mathbf{REL_i = \Sigma\ if\ \ percentDAM - BL_{i,j} > 10\ percent:\ Fa_{i,j} * [\ (1 -\ percentOO_i) * (DC_i) +\ percentOO_i * (DC_i + RENT_i * DT_{i,j})]}$$

REL_i	Relocation costs for occupancy class 1 (in dollars)
$Fa_{i,j}$	Floor area of occupancy group i and depth j (in square feet)
$PercentDAM - BL_{i,j}$	Percent building damage for occupancy i and water depth j, (from depth-damage function), if greater than 10 percent
DC_i	Disruption costs for occupancy i (in dollars)
$DT_{i,j}$	Displacement time (in days) for occupancy i and water depth j (in days)
$percentOO_i$	Percent owner occupied for occupancy 1
$RENT_i$	Rental cost for occupancy 1 (in $\$/ft^2$/day)

Figure 11. Resident Relocation Equation and Variable Explanation

It is important to note that this equation only calculates costs for owners of affected structures. It doesn't incorporate any relocation costs renters may incur when moving- even if temporary. This model also assumes that if the structure is less than 10% damaged as a result of the flooding event that occupants would not permanently relocate, and therefore owners would not lose rental income. Despite these inefficiencies this equation still presents a good picture of the costs that may be incurred due to additional SLR.

The first step was to identify residential buildings that would be newly affected by the increase in SLR rise. CRB has already calculated the cost of relocation in a 36" SLR scenario, and the value found here was added to that figure to calculate the total cost of 48" of SLR. This approach was taken because the steps of the cost analysis often required individualized values by building, and time constraints prevented a larger scale cost analysis.

To identify affected buildings, the team used the BostonGIS 2016 Parcels and Boston Buildings layers, the CRB 36" SLR layer, and the newly created 14' contour layer. Using these layers, all residential homes only affected by the 14' contour line of flooding were identified. The residential parcels layer was clipped to the building file showing only newly affected buildings in order to identify the land use category associated with each building.

Each building in the land use categories of Residential Land, Condominium Master, and Mixed-Use Res/Comm, was then visually evaluated through the use of Google maps street view to determine whether or not residences exist on the property and what floor of the building they were on. All other buildings were assumed to be residential buildings from street level up. The CRB Methodology Appendix indicates that if residences are on the second floor of the building and the building experiences less than 10 feet of flooding, then it does not need to be considered in the resident relocation calculation (CRB). Once confirming whether each building in the newly affected building layer would be considered in the calculation, the team downloaded the building data to secure square footage data.

Once affected buildings were identified, Hazus occupancy classes were assigned to each building using building descriptions from the BostonGIS 2016 Parcels layer. Buildings described as Residential Single Family were assigned to Hazus occupancy class RES1 for single family dwelling. The rest of the buildings were assigned RES3 for multi-family dwellings.

Next, Table 14.11 in the Hazus Technical Manual was utilized to assign each newly affected residential building a percent owner occupancy value. Each home classified as RES1 was assigned 75% for owner occupancy, and each building classified as RES3 was assigned 35% for owner occupancy. To determine the height of flooding in each building, the flood depth map of East Boston was used to assign a flood depth value to each building within the neighborhood. Determining flood depth in each building was essential to assigning depth-damage percentages to each building.

After assigning flood depth values to each building, they were separated into two layers: Homes with less than one foot of flooding and homes with 1-2 feet of flooding. All newly affected buildings fell into these two categories. The Percent Damage Cost for Occupancy was determined by using depth-damage functions (DDFs). Depth damage functions are separated by flood occupancy code and also include a description of the building. For RES1 buildings, the team chose the USACE DDF with description: "two story, slab foundation, structure, salt water, short duration". This was the description that best fit the buildings of focus. For all RES 3 buildings values from the United States Army Corps of Engineering "Apartments, Structure" depth-damage curve was used. Values of percent damage were assigned to each building based on the level of flooding experienced.

In order to calculate the rental cost per occupancy, CRB conducted a rent survey of each neighborhood they assessed. Due to time and resource constraints, the MQP team did not conduct a neighborhood rent survey and instead used the average rent value for East Boston given by Boston Pads. The Boston Pads database contains data on over 150,000 Boston apartments. Disruption Costs for occupancy are listed by occupancy class in Table 14.10 of the Hazus Technical Manual. These values were then assigned to the appropriate building based on the previously assigned Hazus Occupancy class. Flood Restoration Time by Occupancy is found in Table 14.12 of the Hazus Technical Manual. The time, in days, was assigned to each building based on building type and flood depth. Each building FID with corresponding square footage and all other values obtained were compiled into a spreadsheet to then calculate the additional cost of a 1% storm with additional 1ft of SLR on the neighborhood of East Boston.

3.2.3 Additional Business Impacts

Due to resource constraints, the team was unable to follow CRB's methodology for calculating business impacts of a 1% flood event. CRB's methodology for their Business Interruption Consequence Analysis included direct, indirect and induced business impacts. These business impacts included considerations such as loss of sales and employment compensation, the impact of local industries buying goods and services from other local industries, and the response by an economy to a direct effect when income received is spent. An example of an induced impact is the employee compensation payments that are circulated to household spending. CRB used IMPLAN input-output software to model expected economic losses. The team was unable to use this software due to time and resource constraints. Despite this limitation, the team wanted to quantify the business buildings that would be impacted by the additional foot in SLR. To complete this task, the team isolated commercial buildings on the GIS map of SLR that follows the 14' contours. Any building that lay in the additional floodplain was selected and isolated using the "Select By Location Tool". Additionally, upon review of the maps, there were "water locked" buildings within the expected flooding during a 1% annual flood event with SLR at a 14' contour. This means that, during a 1% storm, the buildings will be completely surrounded by water. These buildings were selected and isolated in the same manner.

3.3 East Boston Coastal Resiliency Design

In order to identify a location within Boston to create a SLR protective design for an area, the new flood depth grid and social vulnerability data were combined to identify the most inundated and vulnerable areas of the city. This location was assessed by the team to design a flood protection system to protect a vulnerable population.

3.3.1 Social Vulnerability Assessment

The team used information gathered from the Centers for Disease Control and Prevention (CDC) Social Vulnerability Index (SVI) to spatially understand the locations of vulnerable communities that may be impacted by the higher projected SLR. For the purpose of the project, the team downloaded SVI data for Massachusetts. State census tracts give SVI's relative to the state's vulnerability rather than all of the United States. Each census tract is given a score ranging from 0 (lowest vulnerability) to 1 (highest vulnerability). The score is a combination of the four themes that make up the overall SVI. The SVI data for all four themes and overall ranking were analyzed in GIS to spatially identify locations to prioritize.

3.3.2 Overlay of SVI and Depth Grid

Next, the flood layer encompassing the 14' contours was laid over the SVI map displaying the overall SVI scores for East Boston. A green to blue color gradient applied to the layer shows the change in flood depth throughout the areas. The SVI map was shown in a transparent gradient of green to red to represent the 0 to 1 scale for vulnerability. A map was created for each of the four SVI categories (socioeconomic status, household composition and disability, minority status and language, and housing type and transportation) along with the SVI summary rankings. Analyzing where the two layers overlapped allowed the team to identify the most vulnerable areas of the city.

3.3.3 Distribution of East Boston Planned Flood Protection Projects

After identifying areas with high SVI scores and inundation, the team assessed the distribution of projects within East Boston to identify environmental justice communities currently underserved by the Boston planned projects. The Boston Climate Resiliency Project Tracker developed by CRB was used to identify short-term, mid-term, and long-term projects and those that are currently in development or completed for East Boston. Using this comprehensive tracker, the team proposed a conceptual-level project design to address SLR impacts along Condor Street. This neighborhood has an overall SVI score above 0.79, which is 'high vulnerability' on the maps the team created, will experience future flooding due to SLR and storm surges, and had no planned projects at the time of this study. This project site is also of great interest to GreenRoots, a local environmental protection organization that was in the process of acquiring the parcel of land on which the wall is located. The Condor Street area is in need of future projects that respond to the increase in SLR, the team chose to focus on the area for this reason. In addition to the teams' work will provide insight for GreenRoots' future efforts.

3.3.4 Design Options Alternatives Analysis

The team first identified typical designs used by the City of Boston for coastal resiliency. These typical designs were collected by using the previously mentioned Boston Climate Resiliency Project Tracker and the Climate Resilient Design Standards and Guidelines for Protection of Public Rights-of-Way by the Public Works Department of Boston (BPWD). These included designs such as elevated vegetated berms, elevated harborwalks, deployable flood walls, seawalls and elevated streets. Following a site visit to Condor Street, the team discussed viable options for each flood pathway. Based on the research of typical designs certain options were deemed unrealistic for the project site and not considered during the alternatives analysis. For example, the design solution of a deployable floodwall in place of the existing wall along Condor Street would be unrealistic due to its temporary deployment. After determining viable options in each flood pathway, the team performed an alternatives analysis using a matrix to rank the elements of each project. The elements considered by the team during research of the conceptual design were: protection during 1% annual flood events, environmental impact, cost of the project, community perception, longevity, design feasibility, and operation and maintenance. Three locations of possible flood pathways were identified along the depth grid shown below in Figure 12.

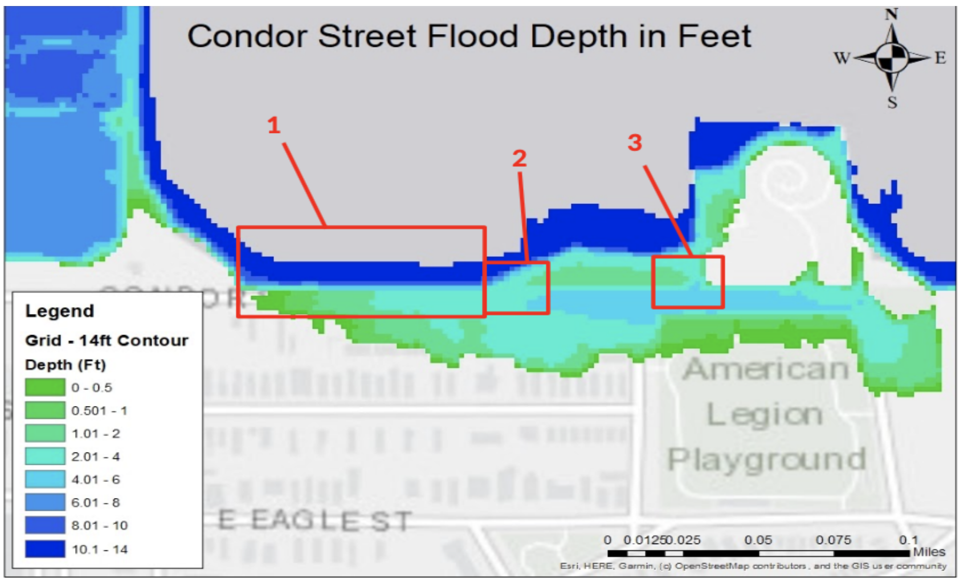

Figure 12. Condor Street depth grid with flood pathways.

The alternatives analysis process was completed in two steps. The first step was to create a table showing design options for the location within the rows and elements of the design within the columns. In each box, a description of the design's impact on the element was written. An example of this process for Location 1 is shown below in Table 2.

Table 2. Phase 1 Alternatives Analysis Example

Design Option	Environmental Impact	Cost	Community Perception	Longevity/ Sustainability	Design Feasibility	Operation and Maintenance
Option	Description of the environmental impact of this option	Cost of option	Community perception of option	Projected longevity of option	Feasibility of option	Cost of operation and maintenance of option
Option						
Option						

The next step was to compare each design based on each of the elements listed above. Each design element was ranked 1 through n (n being the number of design options for the given location) with 1 being the most favorable design element and n being the worst. For example, in Location 1 the environmental impact of "replacing the wall" versus "installing a harborwalk" was compared. Based on the team's research a harborwalk would require relatively larger environmental impact due to building seawards and necessary road construction to integrate the design option. Therefore, "replacing the wall" was given a 1 and "installing a harborwalk" was given a 2. Each element was then assigned a weight; weighting of each element was performed in order to prioritize certain design components over others. If all design components were weighted the same it would potentially skew the results by treating every component evaluated as equally important.

For the purposes of this analysis, the team gave each element of the design a value of 1-3. Here, a rank of 1 represents the most important elements of the design, 2 represents the next most important elements, and 3 represents the least important elements of the design. The team weighted longevity, cost, and design feasibility with a factor of 1. Environmental impact and community perception were weighted with a factor of 2. Finally, operations and maintenance was rated with a 3. The team determined that longevity, cost, and design feasibility deserved a factor of one because they most closely align with CRB's evaluation criteria. The other design elements the team added to have a more detailed analysis of the designs and weighted them with either a 2 or a 3. Environmental impact and community perception were weighted with 2 because any design that compromised the environmental integrity of the region or went against the community's priorities would not be sustainable. Finally, operations and maintenance was given a weight of 3 because these elements are peripheral to the core design. Additionally, while operations and maintenance costs can be high depending on the solution, the benefits of a project that offers protection should outweigh the negatives of the operations and maintenance of the project. Finally, each option was given a weighted total by multiplying the weighting factor by the ranked position. The option with the lowest score was chosen as the favorable option for that location. Table 3 depicts how the second phase of the analysis looked.

Table 3. Phase Two of Alternatives Analysis

Design Option	Environmental Impact	Cost	Community Perception	Longevity/ Sustainability	Design Feasibility	Operation and Maintenance	Weighted Total
Option							
Option							
Weight	2	1	2	1	1	3	

Research performed to determine cost, environmental impact, and all other design elements is detailed in Appendices D, E & F. Using the results from the alternatives analysis, the team provided recommendations for a flood protection system along Condor Street.

3.4 Public Participation Workshop with GreenRoots

In addition to the three coastal resiliency design options that the team recommends, a public outreach program was designed and administered by Hannah Schulz to better understand community perceptions and interests for future neighborhood planning efforts of GreenRoots. When planning for a community, there are many other social factors, not just quantitative information derived from census tracts that can be utilized to work towards solutions. There are also growing concerns of "greening" spaces causing increased gentrification in residential areas. Public outreach and input are an important step when considering any design solution for a community. This public outreach program consisted of a Google form survey distributed to members of the community found in Appendix D, to promote discussion to take place between local residents of Condor Street pertaining to Sea Level Rise, climate change and flooding preparedness.

3.5 Future Recommendations for GreenRoots Efforts

Recommendations for future efforts of GreenRoots can be found in 6.0 Recommendations. This assisted future planning efforts for social justice efforts of GreenRoots and their efforts to protect and serve environmental justice communities.

4.0 Results

The following chapter presents the team's findings in their research and analysis. After reviewing the SVI maps and the CRB 36" flood layer, the team found that East Boston is one of the most vulnerable coastal neighborhoods and will experience increased flooding due to SLR. Additionally, according to CRB's reports, East Boston is one of two neighborhoods that will have the largest percentage of flooding in the near and distant future. The team chose to focus on East Boston for the remainder of the project due to these considerations and time constraints. This chapter includes results from SLR mapping, property damage and resident relocation cost calculations, business effect assessment, and project design for Condor Street. The most important maps are included in this section and additional maps can be found in Appendix E.

4.1 SLR Mapping

Maps of all coastal neighborhoods in Boston were created in GIS depicting 48" of SLR, represented by using the 14' contours. A map of flood depths in the East Boston inundation areas was also created. The depth grid was then used in the Hazus property damage costs calculations as well as in the social vulnerability assessment. The following section details the resulting maps.

4.1.1 Creation of the SLR Maps at 14' Contours

Maps of the 36" SLR with 1 percent chance annual flood layer on top of the expanded 14' contour layer are in Figures 15-18. The city was split into four sections for ease of editing in ArcGIS: East Boston, Charlestown, Dorchester and Mattapan, and Central Boston which encompasses the neighborhoods surrounding the North and South Ends and Back Bay.

The process of following a contour to model flooding is called the bathtub approach and is shown in Figure 13. The bathtub approach does not account for additional flood impacts from increased storm surge, wave motion, tidal, or riverine flooding severity. However, this was accounted for in CRB's approach which explains why CRB's 36" flood layer did not definitively follow the 13' contours, and why assumptions needed to be made to modify the flood layer to reflect 48", or an extra foot of SLR. Simplification of the process was necessary as state-of-the-art flood models such as the BH-FRM developed by MassDOT are not available for public use.

Another reason the 14' contour serves as a close representation of 48" of SLR (and not the 4' contour, as one might expect) is a result of the vertical datum CRB used. It is called NAVD88 and is one of the most commonly used in the United States. A vertical datum consists of known reference points at a certain elevation, usually measured by tidal gages to obtain elevation values of zero, from which many other reference point values are produced in surveying. The NAVD88 datum is 6.5' lower than the Boston City Base. With a sea level rise of 36" during a 1% annual chance flood event, the water elevation would be at around 19-19.5' using the Boston City Base Datum (see Figure 14). Converting to the NAVD88 datum gives an elevation of 12.5-13', which is why the CRB flood layer generally followed this contour in GIS.

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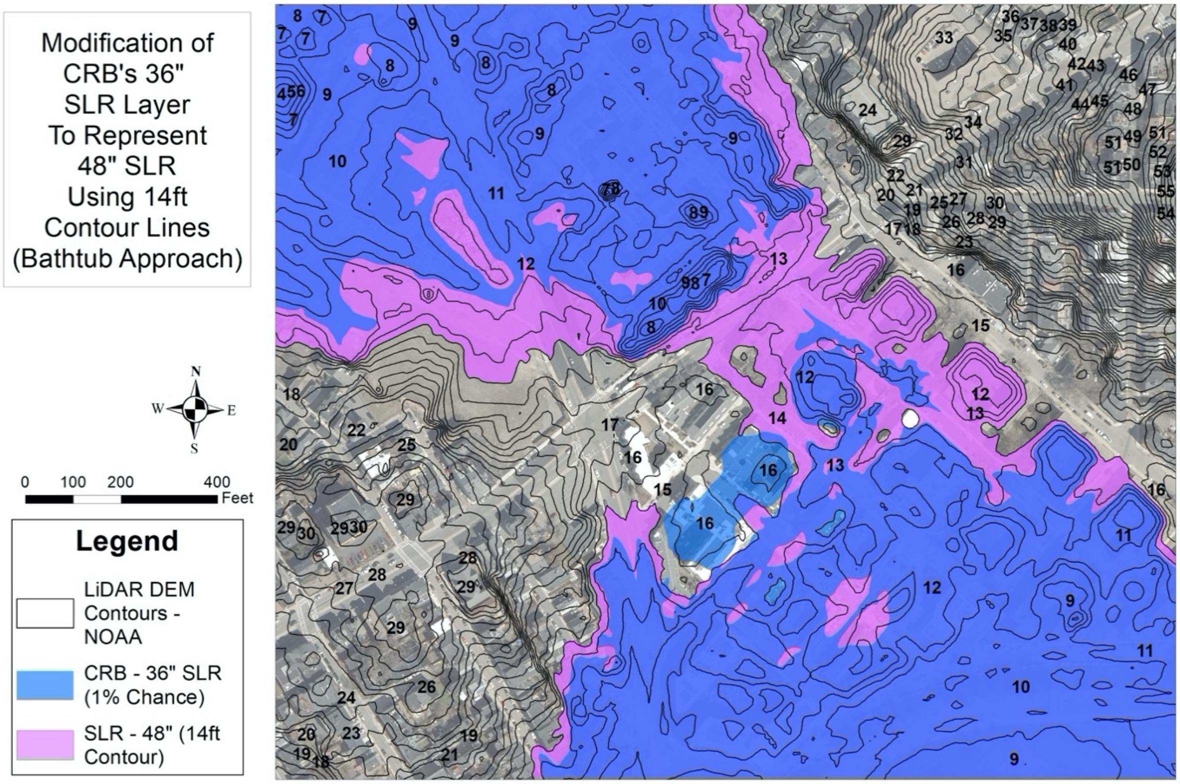

Figure 13. Results from Modifying CRB's Flood Layer

End of useful life	Sea Level Rise Adjustment	1% annual flood event elevation (BFE) *BCB	Minimum DFE for non-critical assets *BCB	Minimum DFE for critical assets *BCB
Baseline	N/A	15.7	16.7	17.7
2030	+9 inches	17	18	19
2050	+21 inches	18	19	20
2070	+40 inches	19.5	20.5	21.5

Notes:
2030: Through 2040
2050: 2041 to 2060
2070: 2061 to 2080
1% annual flood event is also known as the 100-year flood event.
Boston City Base (BCB) Datum can be converted to NAVD88 by: NAVD88 = BCB – 6.46 ft.

Figure 14. Boston flooding elevations (Boston Public Works Department, 2018)

Understanding these uncertainties, there are a number of caveats to be aware of when examining the new inundation maps. First, although CRB included inundation outside of Boston's neighborhood boundaries, the team did not account for any additional SLR in these areas. For example, in the map of Charlestown (Figure 16), flooding extends beyond the neighborhood boundaries. Regardless, these new maps give a strong picture of what inundation will look like with 48” of SLR and allow for new depth grids representative of deeper flood depths to be made.

In Dorchester (Figure 15), the largest area in pink in the center of the map is a low-lying area inland with very small flood pathways from the ocean. This area was left pink because it is highly likely that the space would receive water from other entrances in an extreme storm event, considering tidal surges and wave action.

The map of central Boston (Figure 17) encompasses neighborhoods surrounding the North End, South End, and Back Bay. In this map, the certainty of where additional flooding will happen decreases moving West, as shown by the orange overlay. This is simply a result of the limitations of the bathtub model which doesn’t consider the strength of the water or the amount that is able to reach those inland residential areas. Additionally, there are two dams on the Charles River: The old Charles River Dam built in 1910 at the site of the Museum of Science, and the New Charles River Dam built approximately 2,250 feet downstream of the old. It is certain that both will be flanked and overtopped during a 1% storm event with 48” SLR, but the degree to which this will happen is uncertain based on the team’s available resources. Table 4 details the additional square footage and percent flooding in all evaluated areas.

Figure 15. New Inundation in the Dorchester neighborhood

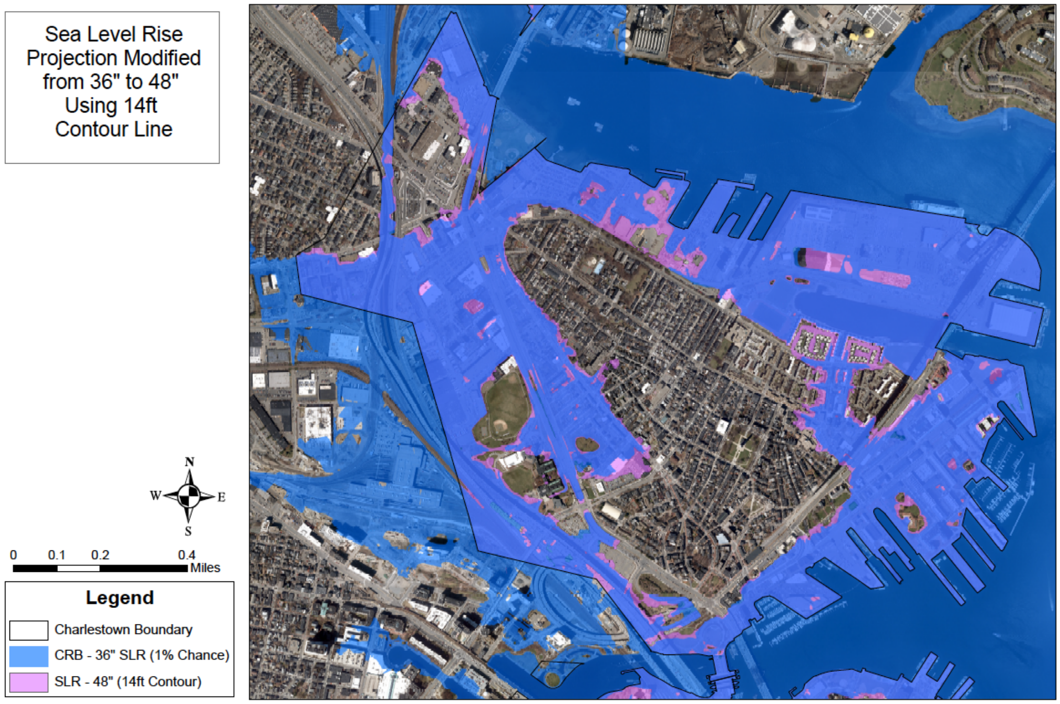

Figure 16. New Inundation in the Charlestown neighborhood

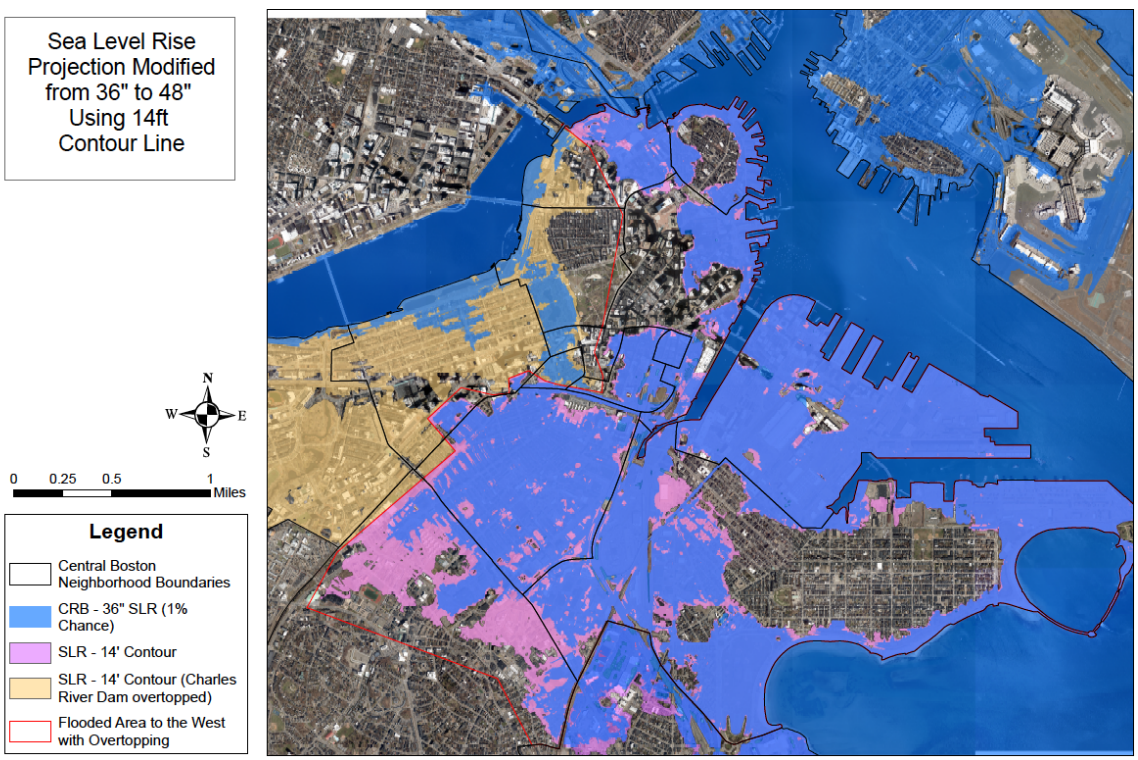

Figure 17. New Inundation in the Central Boston neighborhoods

Table 4. Flooding in Boston with 48" SLR

	Area (sqft)		Percent more flooding
Neighborhoods	36"	48" (14' Contour)	
East Boston (with Logan)	64,598,837	86,036,595	24.9
East Boston (without Logan)	38,848,425	41,604,920	6.6
Charlestown	20,112,235	22,233,804	9.5
Dorchester and Mattapan	32,690,000	33,746,834	3.1
Central Boston (without overtopping)	93,589,758	113,422,720	17.5
Central Boston (with overtopping)	101,532,617	158,680,210	36.0
All (with overtopping and Logan)	218,933,689	300,697,443	27.2
All (no overtopping no Logan)	185,240,418	211,008,278	12.2

Focusing on East Boston, Figure 18 provides a view of all of the neighborhood's inundation, with a closer look at flooding occurring at the Condor Street location in East Boston. The green outlines the boundaries of Logan Airport, where the majority of the additional flooding occurs. Overall, the land owned and operated by Massachusetts Port Authority on which Logan Airport stands accounts for almost 87% of the total additional inundation from an extra 1' of SLR. Including the airport, there is about 33% more flooding in East Boston at the 14' contour than in CRB's 36" SLR scenario. Not including the airport, only about 7% extra inundation occurs compared to the total amount of flooding already happening at 36" of SLR in East Boston.

Figure 18. 14' SLR Overlay with Inset - East Boston

4.1.2 Depth Grid Map for SLR at 14' Contours

A map of East Boston's flood depth with the SLR expanded to 14' contours is shown below in Figure 19. The flooding is represented on a scale of green to dark blue with green being shallow flooding and blue being deeper flooding. Referring to the map, most of the area around the coast is dark blue with 4 or more feet of flooding, while inland flooding is green with less than a foot of flooding.

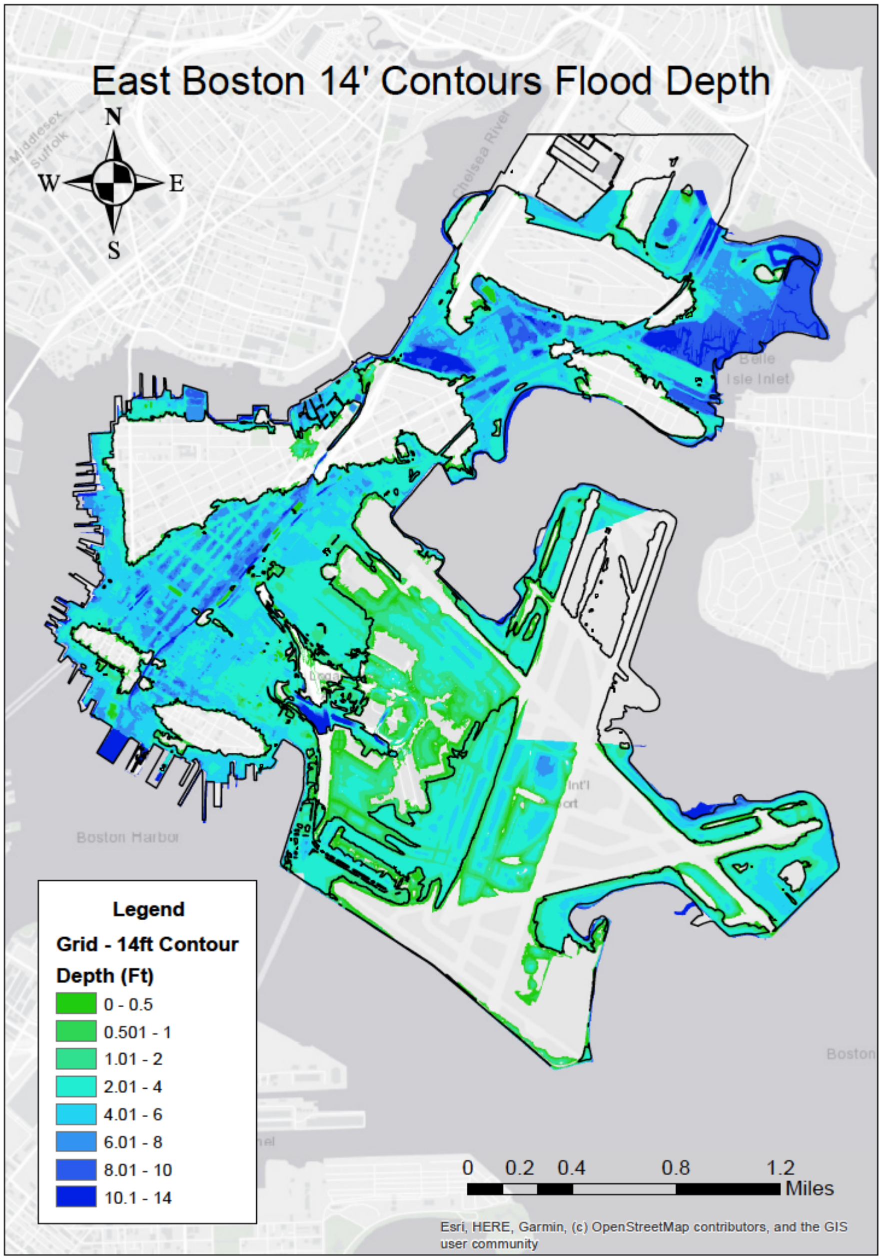

Figure 19. East Boston Flood Depth at 14' Contours

As discussed in the methodology, outliers were removed from the elevation raster before subtracting it from the 14' raster. Elevations below 0 feet were set to be equal to 0 feet. This was done because the elevations on and off the coast were negative values and were throwing off the depth grid. Since these negative values were representative of the ocean's bottom, and not the elevation of the land, they were not important for the project and could be easily omitted. Furthermore, all elevations above 14 feet were set to be 14 feet. This was done since an area with an elevation of 15 feet should have 0 feet of flooding; however, if outliers were not removed, that same area would display as having -1 feet of flooding. Since the analysis did not require how much land would be above water, setting all elevations above water equal to no flooding (0 feet) would not negatively affect the subsequent analysis.

The map of East Boston's flood depth with the 36" SLR scenario is shown below in Figure 20. Compared to the 14' contours map, the existing flooding has quite similar depths. There are a few spots where there is deeper flooding in the 14' contours map such as the coastline north of Logan Airport.

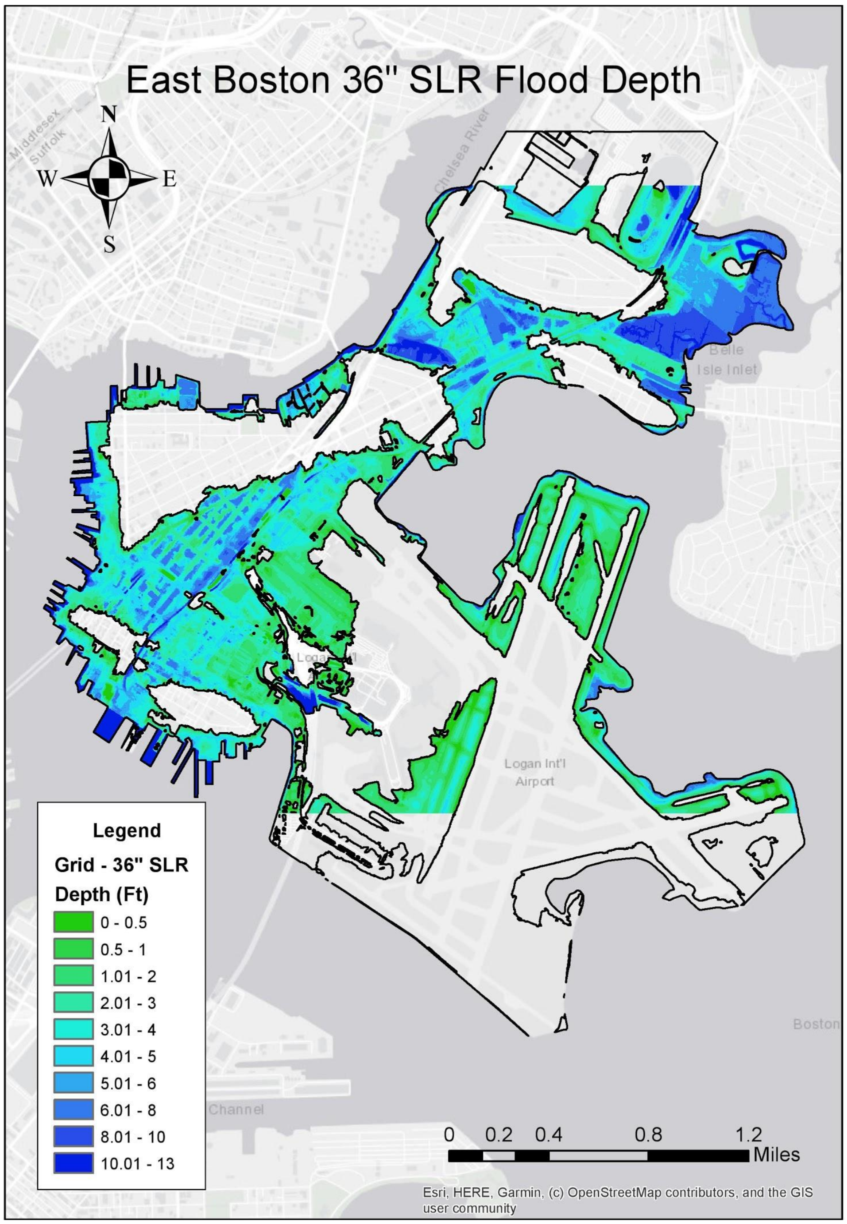

Figure 20. Map of East Boston's flood depth with 36" SLR.

4.2 Impact Assessment

Total losses for a single 1% chance storm event were calculated for both building structure and content damage and resident relocation. The following section contains the results from those calculations, as well as a preliminary quantitative analysis of business effects due to SLR.

4.2.1 Property Damage of Additional SLR at 14' Contours

The team totaled property damage caused by additional SLR at the 14' contour using the Hazus FAST tool. Table 5 contains a summary of the analyses run. The first four columns of Table 5 contain the parameters changed for each run scenario. Additional reasoning and assumptions made for these analyses are listed below the table.

Table 5. Hazus FAST Tool Inputs and Outputs

Depth Grid	Hazus FAST Scenarios	Foundation Type	First Floor Elevation (ft)	Building Loss (USD)	Content Loss (USD)	Total
36"	Riverine	7 - Slab on grade	1	469,530,609	692,775,690	1,162,306,299
36"	Coastal A	7 - Slab on grade	1	510,424,611	752,547,773	1,262,972,384
14ft	Coastal A	7 - Slab on grade	1	603,773,615	882,346,013	1,486,119,628
36"	Coastal A	4 - Basement	4	234,649,523	317,358,268	552,007,791
14ft	Coastal A	4 - Basement	4	307,853,549	416,321,948	724,175,497
36"	Coastal V	4- Basement	4	234,395,405	316,364,519	550,759,924
36"	Coastal A	1 - Pile	7	47,100,736	91,978,796	139,079,532

- Riverine and CoastalV were run to see how the different default DDFs would change the overall damage costs
- Similarly, foundation types were assumed to be uniform for the whole dataset which is a source of error
- Use of a "Pile" for Foundation Type results in a significant underestimation of building and content losses
- Aggregation of multiple building stock files in order to find all required information for the FAST tool resulted in some buildings not having a complete set of required values - these could not be included, which would result in a lower cost estimate
- Time constraints prevented the verification of properties with areas of 0sqft, which could lower the cost estimate
- Time constraints prevented in-depth QA/QC (quality assurance/quality control) of each property Hazus code after initial assignments

CRB lists annualized losses for East Boston in Figure 21. Annualized losses are the cost of a one-time event multiplied by the probability of the event, or percent annual chance. Annualizing losses makes it easier to understand the risk associated with each event. A 10% annual chance event presents much higher risk in terms of flood damage costs than a 1% annual chance event, because statistically the former will happen more frequently and incur more costs. Using this reasoning, the annualized cost associated with a 1% chance storm event with 36" SLR would be roughly $18 million (see Figure 21), which would be divided by 0.01 to give the total cost of a one-time event, a value of $1.8 billion. CRB's East Boston report states that 73% of all losses are building content and structure losses, which yields a one-time event cost for property damage of $1.31 billion.

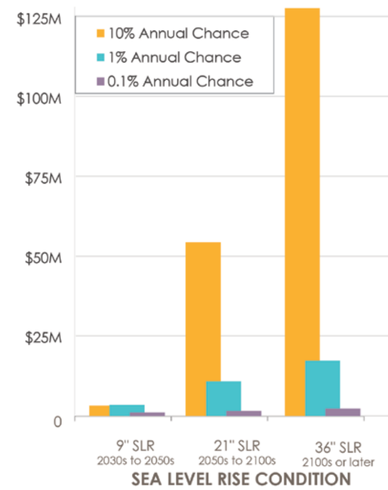

Figure 21. East Boston Annualized Losses

Tables 6 and 7 clearly illustrate the most important outcomes from running Hazus FAST. Comparing a CRB value of $1.31 billion to the team's values, the most accurate analysis scenario at 36" SLR looks to be using the default Hazus foundation type and first floor elevation of Slab and 1ft. The team's value of $1.26 billion is approximately 4% lower, which is very feasible based on the above possible limitations and sources of error. If the same percent difference is applied to the value obtained from the same scenario using the 14ft contour depth grid, damage costs for the new SLR projections would total upwards of $1.54 billion. Using the same ratio of building content and structure losses to total one-time event losses, East Boston could be looking at $2.1 billion in total losses for one flood event by 2070 due to SLR.

Table 6. FAST Results using 36" SLR Depth Grid

Foundation Type	First Floor Elevation (ft)	Total Structure and Content Loss (USD)
Slab on Grade	1	~ $1.26 billion
Basement	4	~ $0.55 billion
Pile	7	~ $0.14 billion

Table 7. FAST Results using 48" SLR Depth Grid

Foundation Type	First Floor Elevation (ft)	Total Structure and Content Loss (USD)	Adjusted Based on CRB Difference (USD)
Slab on Grade	1	~ $1.49 billion	~ $1.54 billion

4.2.2 Additional Resident Relocation Costs at 14' Contours

The map below (Figure 22) shows residential buildings newly affected by the increase in SLR in East Boston. The cost calculated here for resident relocation in East Boston during a 1% storm only includes the costs incurred by the owners of these homes.

Figure 22. Newly Affect Residential Buildings in 48" Flood Layer

The map above shows over 200 homes to be newly impacted by flooding in this storm scenario. The original estimate of impacted residential buildings from CRB was 2,094. The team found that this number would increase to 2,295 given the increase in SLR.

The total additional cost incurred by flooding in these additional 201 homes was found to be $276,000. The initial cost projection produced by CRB for all relocation costs (which includes commercial buildings) in the neighborhood of East Boston was around $54 million. CRB's cost includes not just resident relocation costs but also business and other costs surrounding relocation during a 1% storm event. The team's calculated cost is an additional relocation cost to be incurred during a 1% storm with an extra foot of SLR but does not represent total relocation costs for East Boston. It is important to keep in mind the assumptions made about variable values pertaining to the relocation equation. The value obtained for resident relocation costs during a 1% storm event with 48” of SLR reflects these assumptions.

<u>4.2.3 Additional Business Impacts at 14’ Contours</u>

As mentioned previously in the Methodology, CRB’s methods could not be used to determine business impacts due to limited accessibility to IMPLAN economic modeling software. To identify affected commercial buildings, the team used the BostonGIS 2016 Parcels and the Boston Buildings layers. The Parcels layer was clipped to include just commercial areas. The Building's layer was then clipped to these parcels to show just commercial buildings in East Boston. This contained 980 commercial buildings within East Boston. The amount of newly affected commercial buildings in East Boston went from 626 to 685 from the 36” to 48” SLR. This means 59 more commercial buildings would be affected due to the extra foot of SLR. Additionally, 253 “water locked” commercial buildings were identified, meaning the buildings were completely surrounded by flooding with no access to an evacuation route. The locations of these buildings are shown in Figure 23. The orange dots indicate the newly affected commercial buildings in the 48” flood layer, and the yellow dots indicate the “water locked” commercial buildings.

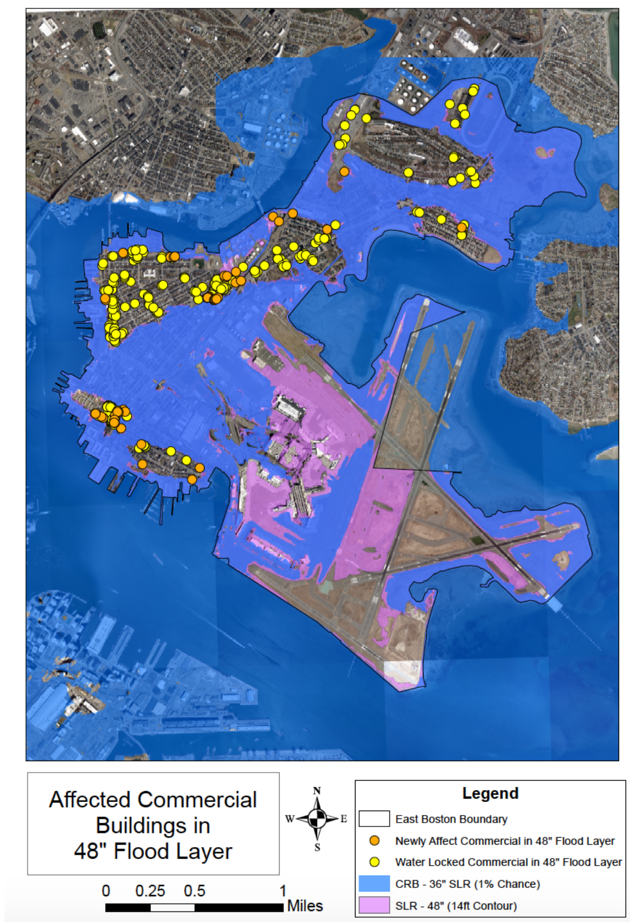

Figure 23. Affected Commercial Buildings in 48” Flood Layer

While the extent of economic impacts of businesses such as direct impacts, indirect impacts and induced impacts could not be accounted for, these preliminary numbers of businesses are an important consideration. According to CRB, 3,080 buildings will be affected during a 1% storm event with 36" of SLR in 2070 or later. Of the buildings newly affected in all of Boston, 9% are commercial. Therefore, it is estimated that 278 commercial buildings within East Boston will be affected by the 36" SLR 1% storm event in 2070 or later. The team's 626 commercial buildings with 36" SLR 1% storm event is significantly larger than the estimated 278. This discrepancy in data may be due to the fact that a commercial parcel may be defined as commercial but does not necessarily have a business on the property. For example, the property could be storage or not currently in operation. Due to limited time constraints for the project, the team was unable to perform QA/QC to confirm an active business was located on the commercial parcel. The 59 newly affected commercial buildings with a 48" SLR 1% storm event appears to be a reasonable increase with the assumptions made by the team. Ultimately, as the flood plain expands with SLR, informing stakeholders with known risk for significant flooding, damage or inaccessibility during a storm is necessary to justify future planning efforts.

4.3 Condor Street Design

After narrowing the project scope to conduct an impact assessment of a 1% storm event only for East Boston, the team chose a more specifically vulnerable area of East Boston for the design component. The following section explains the reasons why the team focused on Condor Street. The team considered the social vulnerability assessment (SVI), the SLR depth grid map, and an assessment of the planned projects in the area. Additionally, this section details the alternatives analysis that was conducted. This alternatives analysis is a weighting and ranking system to compare design options for flood pathways along Condor Street to determine the best flood protection system.

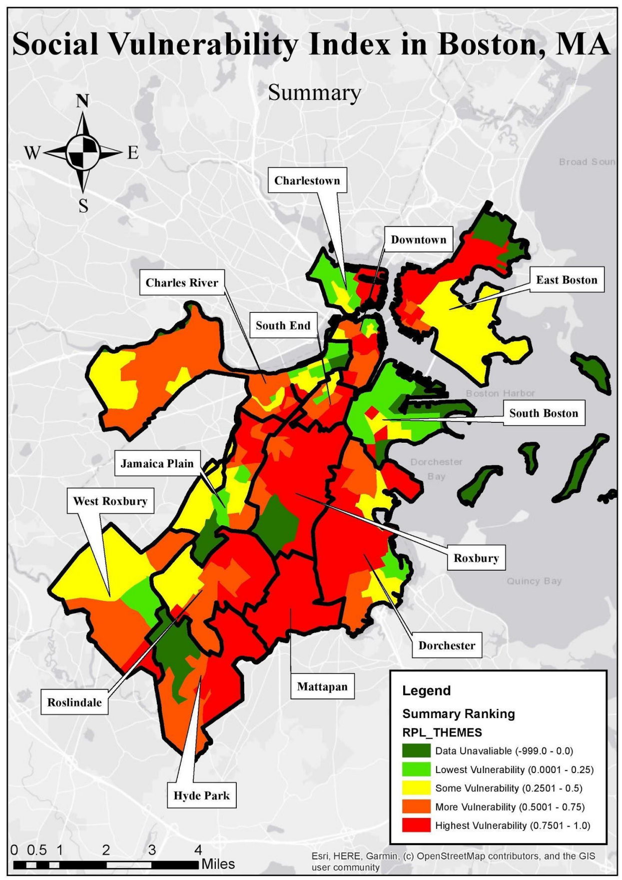

Figure 24. Map of social vulnerability in East Boston

4.3.1 Social Vulnerability Assessment Outcome

Color gradients show SVI data for each census tract of Boston. The map shown in Figure 24 displays the overall SVI scores in green, yellow, orange, and red. The darkest green represents the lowest SVI score, the red represents the highest SVI score. The map is a summary of the four themes including housing type and transportation, minority status and language, socioeconomic status, and finally household composition and disability — all of which have been factored into the SVI. The team also considered the maps of Boston that lay out each individual SVI theme separately. Refer to Appendix E for links to maps of each of these four vulnerability categories.

The team first looked at Constitution Beach and along Route 1A in northernmost East Boston. The overall SVI score deemed this area as highly vulnerable, most impacted by the housing and transportation theme. However, CRB has developed a conceptual level coastal resiliency infographic for Constitution Beach including a stepped harborwalk, and the Route 1A land area is an expansive area stretching over a half a mile of needed protection. The team wanted to create a coastal resiliency project where no projects were being considered by CRB to be planned or developed in order to emphasize an area of Boston where there has been no consideration by the city.

Looking at other highly vulnerable areas in East Boston that still needed help with responding to the increase in SLR, the team then considered the Condor Street neighborhood. On the East Boston SVI maps, Condor Street is ranked as 'high vulnerability' in the overall summary map, 'high vulnerability' within the socioeconomic map, 'more vulnerability' in the household composition and disability map, 'high vulnerability' in the minority status and language map, and 'high vulnerability' in the housing type and transportation map. In addition, designing a flood protection system for Condor Street would provide the opportunity for GreenRoots to benefit from the design considerations. The timing of the project was a driving force that prompted the team to focus on Condor Street, where the project would be much more manageable and the site could be developed with a well-rounded coastal resiliency design for the unprotected area.

4.3.2 SVI & Depth Grids Maps

The map in Figure 25 illustrates the intersection of social vulnerability and flooding. Areas of high vulnerability and deep flooding are shown in a dark purple color. These are considered the most vulnerable areas of the neighborhood both socially and in terms of flooding.

Of the areas in dark purple the team identified locations that did not have any projects planned by CRB to mitigate flooding. These areas include Constitution Beach, Route 1A, and the Condor Street neighborhood. Of these areas the team selected the Condor Street neighborhood to develop a conceptual coastal resiliency design. The team chose this neighborhood because of the high levels of vulnerability exhibited and Hannah Schulz' connection to a local environmental advocacy group that was looking for a way to protect the area from the effects of SLR.

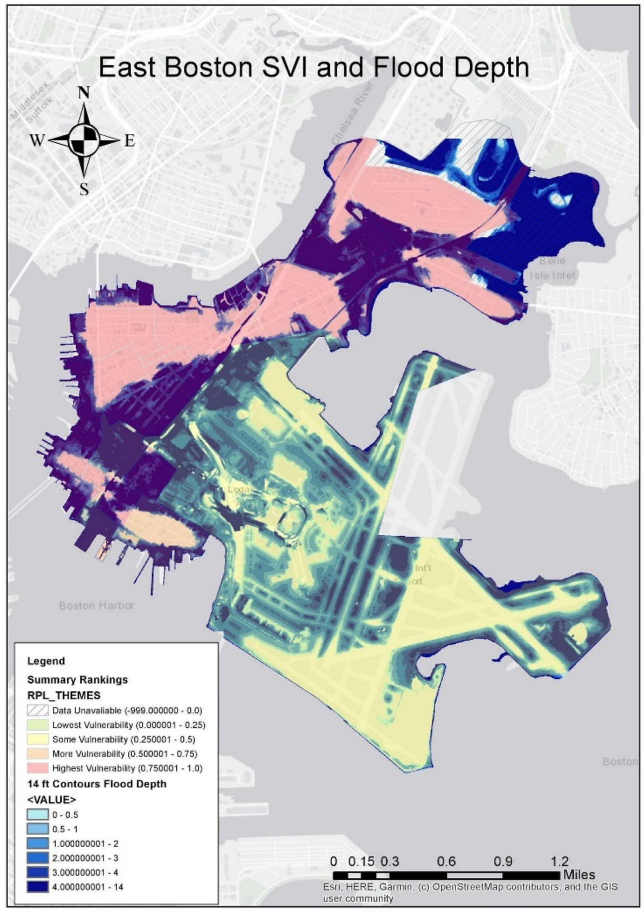

Figure 25. Map of East Boston's social vulnerability overlaid with depth grid to 14' contours

Refer to Appendix E for maps of each of the four vulnerability categories with the SLR expanded to 14' contours depth grid (socioeconomic status, household composition & disability, minority status & language, and housing type & transportation). When compared to the 36" SLR flood depth map, it was found that residents on Condor Street will experience more flooding with the new SLR predictions.

When looking at the Condor Street neighborhood within the CDC's Social Vulnerability Index maps, minority status and language is where the neighborhood was ranked as most vulnerable, as shown in Figure 26. The housing type and transportation theme was the next highest vulnerability, followed closely by socioeconomic status. Household composition and disability was last, meaning the community was least vulnerable due to this theme.

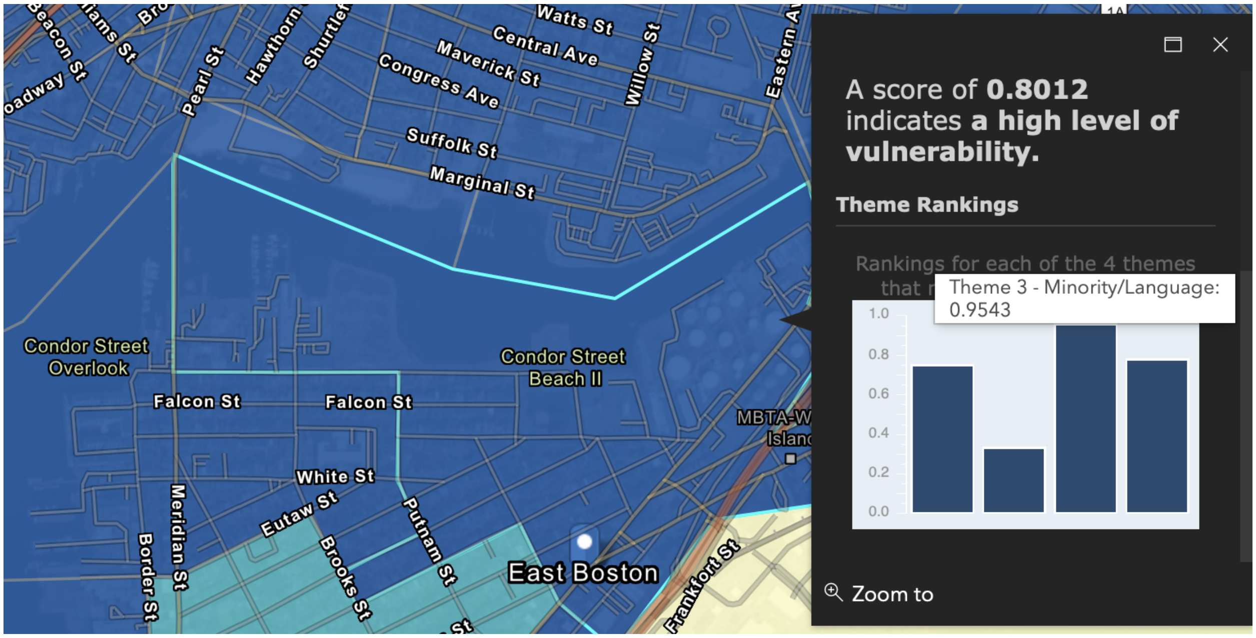

Figure 26. Condor Street SVI Theme Rankings

4.3.3 Stock of East Boston Planned Projects

In East Boston there are a number of projects that are planned in order to respond to the increase in SLR. The projects were developed by CRB and range from short-term (next 5-10 years), mid-term (next 10-15 years), and long-term (next 20+ years). For organizational purposes the team reviewed planned projects starting at Jeffries Point (marked by a star in Figure 27) and moving in a clockwise direction along the coast of East Boston, starting with Figure 27, moving to Figure 28, Figure 29, and finally Figure 30.

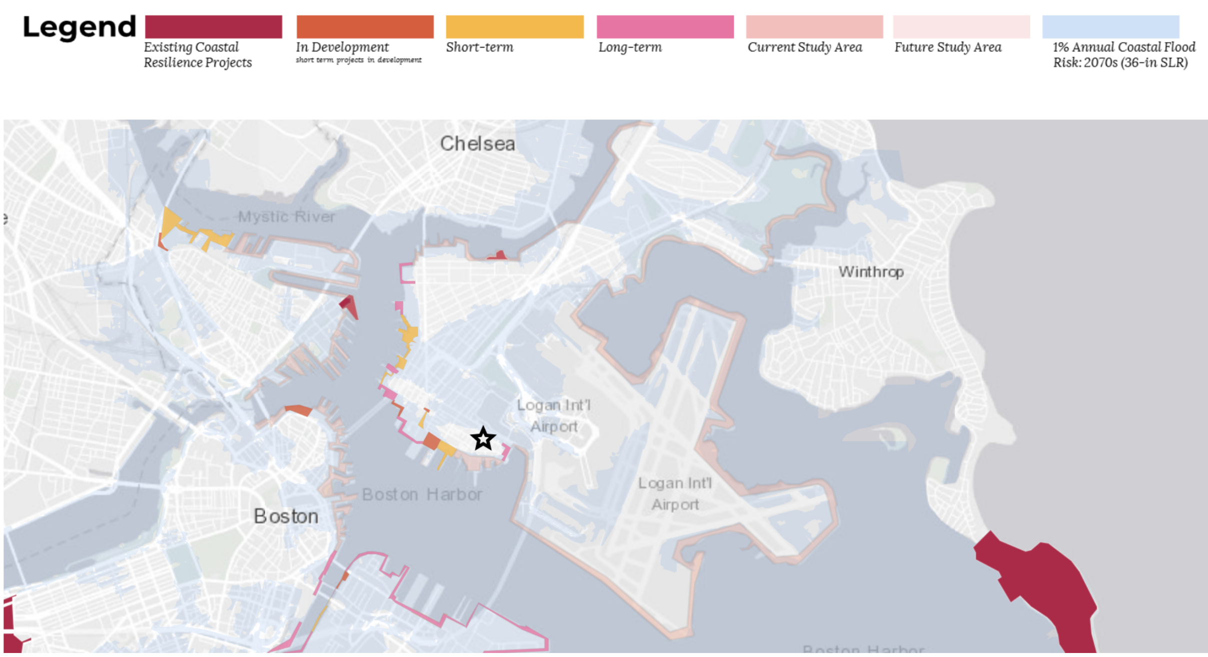

Figure 27. Overview of East Boston Project Tracker

Starting in Jeffries Point in Figure 28, Porzio Park is a long-term project with the goal of adding elevated waterfront parks and plazas. Neighboring the Porzio Park project, there is a future study area that will be looked at by the Massachusetts Port Authority (Massport). Massport owns and operates several airports in the state, including Logan Airport, which is another section of East Boston that is indicated by CRB as a future study area. For the purpose of this project, climate resiliency for Logan Airport was not considered as there is a flood operations plan in place for that area. This plan includes the acquisition of temporary flood barriers, electrical and mechanical systems placed on roofs or levels above flood levels, installing sensors and pump systems, and construction of systems to anchor flood fencing and barriers in the case of a large storm (Massport, 2018). Similar to Porzio Park, the Piers Park 1 Retrofit project also includes the addition of an elevated waterfront park but is a short-term project.

Figure 28. Jeffries Point, East Boston Project Tracker

To the west of Jeffries Point is Piers Park 2 — a project currently in development and will elevate the Greenway entrance (Figure 29). The Greenway entrance also consists of a separate short-term project that, in collaboration with Piers Park 2, incorporates flood protection for an additional 300 residents and a fire station in Jeffries Point. The Greenway floodwall, currently in development, is a deployable floodwall that would provide immediate protection to around 4,300 residents, 70 businesses, and other critical infrastructure. The Clippership-Portside is a long-term project that will add elevated waterfront pathways and a vegetated berm. The Clippership-Hodge Berm is a project currently in development that includes elevating the Harborwalk in combination with a deployable floodwall that will protect nearby residents, housing, and the MBTA Maverick Station. Neighboring Clippership-Hodge Berm, there is a long-term project for LoPresti Park that includes the

Figure 29. West of Jeffries Point, East Boston Project Tracker

development of an elevated waterfront park. The beginning of the Border Street projects starts on the southwest side of East Boston and ends in the west of East Boston.

As shown in Figure 30, moving up the west side of East Boston, with the New Street long-term project and the Border Street short-term projects, the area will include many new elevated waterfront parks, plazas, docks, and vegetated berms in the future. The Border Street projects also aim at addressing community objectives for open space, mobility, and green space access. Similarly, the Mario Umana School long-term project will also include the addition of docks and nature-based features.

Figure 30. West Side of East Boston, East Boston Project Tracker

Looking at the northern extent of East Boston, as shown in Figure 31, Shore Plaza is a long-term project that will include the addition of elevated and vegetated berm. Neighboring the Shore Plaza project, there is a large area of the coastline that is designated a future study area by Climate Ready Boston. Within the future study area, there is a completed remediation project, Urban Wild, on Condor Street, represented by the red area in Figure 31. It was previously an urban brownfield transformed into a natural area that is publicly accessible. The project included the addition of walking paths, meadow grasses, a boardwalk, a viewing path overlooking the river, and a salt marsh.

Figure 31. North Side of East Boston, East Boston Project Tracker

In order to spatially understand social vulnerability, depth of inundation, and Boston's planned projects, Figure 32 was created to show the short- term and long-term projects represented with a red dot overlaid with the SLR to 14' contours depth grid and SVI summary rankings. While CRB has planned for projects in most of the areas of East Boston that will experience very deep flooding, CRB has no planned project for Condor Street, where many residents will experience flooding.

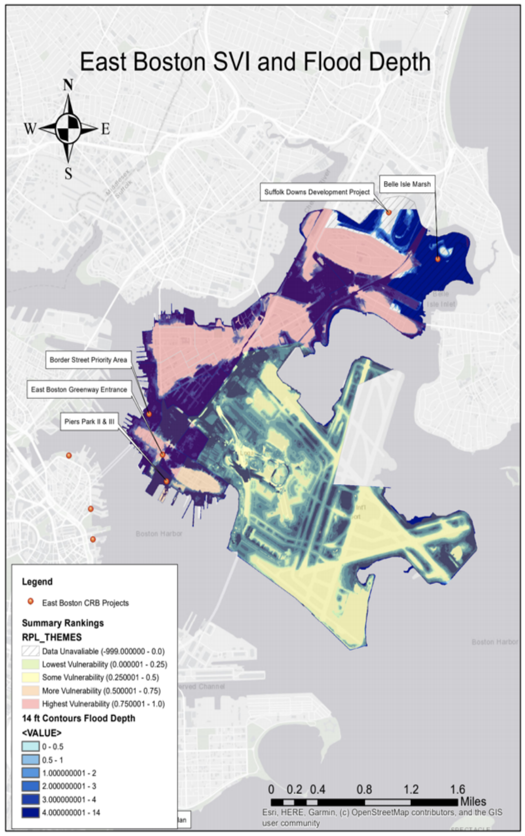

Figure 32. Map of East Boston SVI and Flood Depth with CRB's planned projects

During the engineering process, it is imperative to consider ethics, especially when designing for the community. For this project, ethical considerations such as gentrification were given due consideration. This is because, with increased projects and funding allocated to infrastructure improvements, there are implications of neighborhood appeal. This is also true when an area becomes more sustainable and more green space is added. Large developers may move into an area, increasing demographics with higher income thus driving higher rates of rent and higher prices of food. Gentrification and the idea of "greenifying" a space to the point that local residents are forced from their homes must be considered from a policy standpoint to ensure residents are equitably served. One way to combat this is by educating residential owners of the worth of their homes. Developers can take advantage of lower income residential owners by offering deceivingly high offers for land when in actuality residents are unfairly compensated due to lack of understanding of future property value.

<u>4.3.4 Design Options for Coastal Resiliency</u>

After selecting an area to focus on for a conceptual design within the neighborhood of East Boston, the team completed an alternatives analysis. The purpose of this analysis was to compare and contrast each potential design option against one another. In order to develop the best design for each identified flood pathway, the selected location of Condor Street was divided into three sections seen in Figure 33.

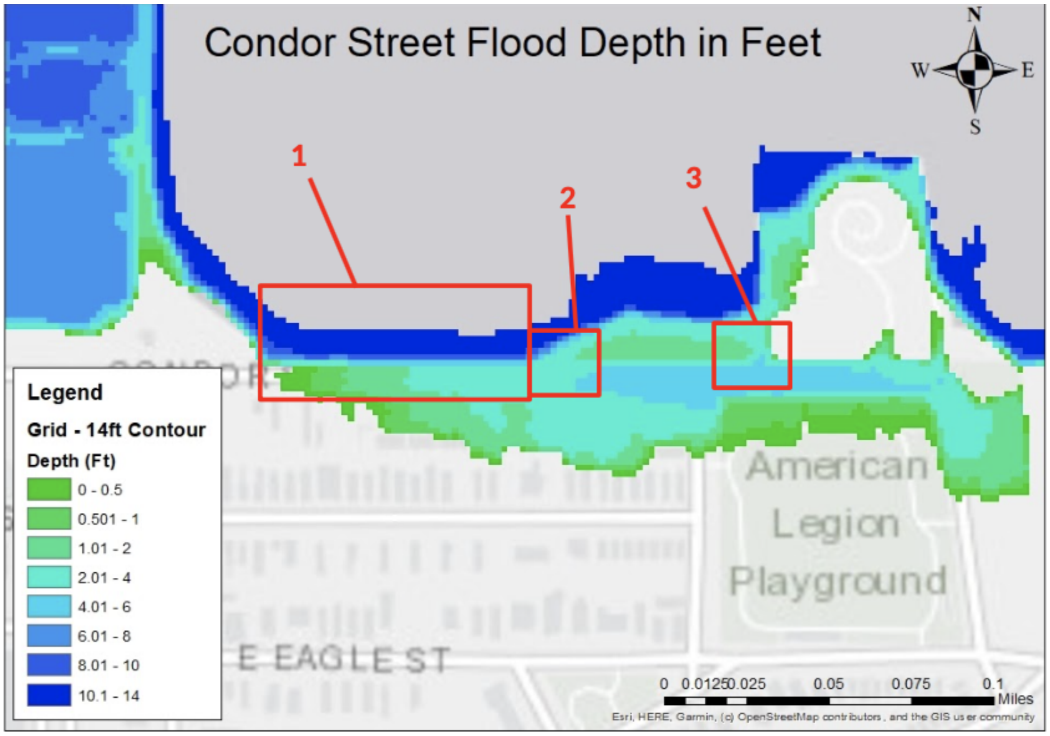

Figure 33. Flood depth map of Condor Street Divided by flood pathway

The first major flood pathway identified during the site visit was the wall along Condor Street. This wall borders a section of Condor Street near Urban Wild. The site visit revealed that much of the wall was in disrepair including crumbling along the top of the wall as well as severe erosion and crumbling at the base of the wall. Figure 34 below shows the extent of the damage along the top of the wall, and Figure 35 shows the damage to the base of the wall caused by erosion.

Figure 34. Erosion at Base of Wall

Figure 35. Wall Damage

It is important to note that currently, SLR projections do not show flooding overtopping the Condor Street wall. However, due to its current condition, it is likely the wall would not be able to withstand much wave action or flooding. If the wall were to collapse during a flooding event, there would be a significant impact on the surrounding neighborhood. For these reasons the wall at Condor Street was considered a significant flood pathway.

The next two flood pathways identified were the two entryways to Urban Wild Park closest to the wall on Condor Street. Urban Wild is a remediation project that took place in 2003 to create a public park out of a contaminated brownfield site. Both entryways are projected to be flood pathways with the additional 1ft of SLR. Figure 36 below shows the entrance of Urban Wild at Location 2, while Figure 37 shows the entrance at location 3.

Figure 36. Location 2 Entrance

Figure 37. Location 3 Entrance

After establishing the three main flood pathways the team completed three separate alternatives analyses for designs at each location. In the initial step of the analysis, the team researched design options to develop a better understanding of how the designs compared to each other based on the following six elements: environmental impact, cost, community perception, longevity/sustainability, design feasibility, and operation and maintenance. This initial step informed our choices for the second phase of the analysis: the weighted ranking. Table 8 provides information for qualitative assessments of each design element. For more information pertaining to the weighted ranking system, see the Methodology within section "3.3.4 Design Options Alternatives Analysis." Additionally, Appendices D, E and F contain detailed information and explanation of sources and reasoning used for each ranking. It is important to note that the main goal behind the alternatives analysis was to perform a broadly accurate comparison between design options as opposed to a high level of precision for each design.

Table 8. Design Element Level Explanations

Environmental Impact	Community Perception	Longevity/Sustainability	Design Feasibility
Low: This design will have little to no impact on the environment	Good: Existing data indicates that this design would be very desirable to the community	Extensive: This design has a lifespan of 50-100 years or more	Good: The chances of the design being approved for construction and implemented is high
Medium: The design will have some mild impacts on the environment	Fair: Existing data indicates the community may like this idea, although it does not fulfill all wants and needs	Moderate: This design has a lifespan of 25-50 years	Moderate: The chances of the being approved for construction and implements are moderate
High: This project will have extensive impact on environment	Poor: Existing data indicates community members would find this design unfavorable	Limited: This design has a lifespan of less than 25 years	Difficult: The chances of the being approved for construction and implements are moderate are low
None: The environmental impact of this design could not be found or does not apply here	None: The community perception of this design could not be found or does not apply here	None: The Longevity/ Sustainability of this design could not be found or does not apply here	None: The design feasibility of this design could not be found or does not apply here

The team first considered design options at Location 1. The corresponding "Table 12. Alternatives Analysis Results at Location 1" describing research, sources and assumptions behind the rankings of each design option element can be found in Appendix F. The teams final weighting and ranking is seen below in Table 9.

Table 9. Location 1 Weighted Ranking

Design Options	Environmental Impact	Cost	Community Perception	Longevity/ Sustainability	Design Feasibility	Operation and Maintenance	Weighted Total
Replace Existing Wall	1	1	2	1	1	1	12
Elevated Harborwalk Along wall	2	2	1	1	2	2	17
Weighting Factor	2	1	2	1	1	3	

The first element of design evaluation was the Environmental Impact. In Location 1, it was determined that an elevated harbor walk and reconstruction of the Condor Street wall would have similar, high, environmental impacts. For both designs, the trees along the wall would need to be removed. These trees, if not removed, would continue to grow and impact the structural stability of the wall. Significant fill would be required after the removal of the trees and grasses along the shoreline. While the environmental impact is high for both options, the elevated harbor walk would require significantly more construction and armoring of the coast. Due to site constraints, an elevated harbor walk would require elevation of the adjacent sidewalk and expansion seaward to account for a small vegetated berm to grade down to street level. For this reason, replacing the wall was ranked lower for environmental impact as it would have a smaller impact on the project site's environment.

The next element evaluated was the cost of the design. Our research indicated the replacement of the existing Condor Street wall would cost significantly less than the creation of a harbor walk (Boston Public Works Department, 2018). Therefore, the Condor Street wall replacement design was given a lower value for cost. Next, feedback from CRB's open houses in East Boston was reviewed to gauge community perceptions of and preferences for flood mitigation designs. The team recognizes that this information may not be an accurate reflection of the true feelings of those who live in the community surrounding Condor Street. However, most community feedback throughout the city echoed similar sentiments of positive views of green space and any projects that mitigated flood impacts in the area. Before any solution is implemented in the area, the community should be surveyed for feedback on the design. This consideration was pursued by Hannah Schulz in a subsequent report. Despite the inefficiencies in this data, the team used it to infer that the community would have a more favorable view of the elevated harbor walk design. This design involves greater community aesthetics and the addition of a multi-functional space to view the water rather than simply replacing the existing wall. For these reasons, the elevated harbor walk was given the rank of one in the weighted analysis.

Next, the longevity and sustainability of each design was evaluated. The team researched common life span predictions for other similar walls and harbor walks. Research indicated that the two designs had similar, extensive life spans of 50-100 years (Boston Public Works Department, 2018). As both life spans were the same, each design received a one in this category for the weighted ranking. Design feasibility was based on the logistical considerations of the design implementation. In the case of the harbor walk, logistics would need to be considered including involvement with the Army Corps of Engineers when building seaward, disruption of local traffic patterns in the case that the road needs to meet the elevation of the harbor walk, significant funding considerations, and complex stormwater design would be needed for an elevated walk which could inadvertently trap water at street level during precipitation events.

Finally, the annual cost of operation and maintenance for each design was estimated to determine which design would be least expensive to maintain. Research helped determine that the wall along Condor Street would be less expensive to maintain and therefore was given a one (Boston Public Works Department, 2018).

All of this information was compiled, and the designs were ranked and then weighted appropriately to determine the best design for Location 1 would be to replace the existing wall along Condor Street.

The same process was repeated for Location 2. The corresponding "Table 13. Alternatives Analysis Results at Location 2" describing research, sources and assumptions behind the rankings of each design option element can be found in Appendix G. Below is Table 10 with the weighted ranking by the team in Location 2.

Table 10. Location 2 Weighted Ranking

Design Options	Environmental Impact	Cost	Community Perception	Longevity/ Sustainability	Design Feasibility	Operation and Maintenance	Weighted Total
Deployable Floodwall at first entrance to Urban Wild	1	2	2	1	1	1	13
Elevated pier at corner of wall and Urban Wild	3	3	1	2	3	3	25
Elevated Vegetated Berm	2	1	3	1	2	2	20
Weighting Factor	2	1	2	1	1	3	

The design option of a deployable floodwall would require the construction of a retention wall to the left of this entrance to Urban Wild. The deployable floodwall is temporary and would only be put up during a severe storm event. The design option of a vegetated berm would require raising the berm across the walkway to eliminate the flood path entirely. The elevated pier would be built at the corner of Urban Wild at Location 2 to prevent inundation via the park entrance. Of these options, the deployable floodwall has the lowest environmental impact as it involves minimal permanent changes to the current area. The next highest environmental impact is the vegetated berm, built across the pathway. While this still has an overall low impact on the environment, it does involve more changes to the existing landscape than the deployable floodwall. Finally, the highest environmental impact is the elevated pier as it involves significant construction, grading, piling installation, and building the coastline outwards.

The cost of each design was then researched to inform our cost rankings. Research revealed that the vegetated berm would cost the least, the deployable floodwall would be the next most expensive, and lastly the elevated pier would be significantly more costly than the other options (Climate Ready Boston, 2016, p. 26).

Existing community feedback from a forum conducted by CRB in 2017 was used to inform the rankings of community perception for each option. The elevated pier at the corner of Urban Wild would likely be the most favorable design for residents, as it creates additional community space and expands Urban Wild's community space. The next most favorable design would likely be the deployable floodwall because while it does not add any green space, it still offers protection to the neighborhood and leaves the existing green space intact. The least favorable option would be the elevated vegetated berm as the installation of this design would result in the loss of an entryway to Urban Wild (Climate Ready Boston, 2017).

Both the deployable floodwall and vegetated berm designs have extensive lifespans of over 50 years, and consequently tied for the rank of one in the category of longevity/sustainability. While the elevated pier would be a strong design, its extension off the coastline makes it significantly more vulnerable to damage from wave action during strong storms.

Design feasibility considerations are the greatest for the elevated pier, as this option requires the most detailed and time-consuming construction. The pier must be designed to block SLR from entering Condor Street and also be structurally sound in an intense storm event. By contrast, a vegetated berm requires less construction but presents a challenge in keeping the entrance at Location 2 ADA accessible at the same time as being high enough to block water. The floodwall presents the least complications which is why it was ranked as the most feasible design out of the three options.

Finally, the cost of operation and maintenance of each design was tabulated and the designs were ranked accordingly, with the deployable floodwall requiring the least annual operations and maintenance costs. Factoring in all of these elements, the deployable floodwall ranked as the best design solution for Location 2.

Despite the research conducted and analysis performed to determine the best design solution for this location, there are still some gaps in this assessment. The cost of operations and maintenance here does not account for the specific challenges of a deployable floodwall. One such logistical difficulty involves the installation of a small wall in one area of a much larger city during an extreme storm. The city likely would have bigger issues and emergency planning procedures to allocate time and resources to. While this is a logistical concern for the floodwall, this can also be seen as an opportunity to engage the community and implement a strategy that empowers members of the community to deploy the floodwall in the case of a storm event.

The analysis for Location 3 was similar as several of the same design options were considered. The corresponding "Table 14. Alternatives Analysis Results at Location 3" describing research, sources and assumptions behind the rankings of each design option element can be found in Appendix H. Below is Table 11 with the weighted ranking by the team in Location 3.

Table 11. Location 3 Weighted Ranking

Design Options	Environmental Impact	Cost	Community Perception	Longevity/ Sustainability	Design Feasibility	Operation and Maintenance	Weighted Total
Elevate vegetated berm in front of entrance	2	1	3	2	2	2	19
Deployable floodwall at entrance	1	2	1	1	1	1	10
Storm grate connected to a small wet well and a drainage pump	3	3	2	3	3	3	25
Weighting Factor	2	1	2	1	1	3	

The environmental impacts of a vegetated berm and deployable floodwall were previously mentioned and are both relatively low. The idea behind the design option of a storm grate connected to a drainage pump and tank is to redirect rather than block the water. This would require extensive construction and installation of a new well, drainage pipe, and tank for temporary storage in the area. The stormwater drainage system in the area is currently gravity fed to an outlet in the same location that would cause inundation in a storm event. For this reason, environmental impact and cost would both be much higher for a storm grate system than a floodwall or vegetated berm.

It is hard to be certain without community input on these specific design options; however, one can infer that between two solutions that will both serve the same purpose of protecting against flood damage, the least costly option would be favored. As previously mentioned, a deployable floodwall that leaves existing greenspace nearly intact would be most favorable, followed by a vegetated berm, and last, the storm grate system due to cost and construction implications.

Research showed that the longevity and sustainability of all three design options is extensive, ranging from offering 50-100 years of protection. A vegetated berm would be the most sustainable option, only requiring the use of additional fill. A storm grate system could add to its longevity with the likelihood of being useful for other purposes besides redirecting SLR during a storm, such as water storage during extreme precipitation. The height of a deployable floodwall can be adaptable to accommodate higher flood levels, adding to its longevity. For these reasons, all options were given the same ranking.

The design feasibility of the storm grate would be significantly more complex than the implementation of a deployable floodwall or incorporation of an elevated vegetated berm. The team ranked the storm grate at a 3 due to the implications of requiring a small pump and generator. The existing gravity-fed stormwater system along Condor Street would be ineffective with significant flooding, because the outfall is along the coast and would not allow for any discharge to that area. The vegetated berm was then ranked at 2 because of the feasibility associated with construction of a berm, and logistics of impacting the entrances to Urban Wild. For ease of deployment and the little change in day-to-day function of the Urban Wild entrance, the deployable floodwall was ranked as 1.

Operation and maintenance costs of a storm grate system are also significantly higher than those of a vegetated berm or deployable floodwall. The floodwall requires the least operation and maintenance costs, and all three options were ranking accordingly. All elements considered; the floodwall came out as the best design option for Location 3.

After extensive analyses of all design alternatives for each location, the best options to protect inundation near Condor Street are replacement of the entire wall along Condor Street and the installation of deployable flood ways at each of the two flood pathway entrances to Urban Wild. Together these designs protect the area from the projected flooding caused by SLR.

Limitations during research affected the accuracy of cost estimates for different design options. Permitting was not considered as a ranked element to compare and contrast between design options. However, there will have to be significant consideration of permitting when developing a project. According to the Boston Public Works Department, a permitting strategy should be developed for a project to understand federal, state and local regulations and requirements. Permits, schedules and costs for the flood protection design should consider different agencies regulations. These different regulations may include the Boston Planning and Development Agency Article 80, Coastal Zone Management (CZM) review, FEMA review, Massachusetts Emergency Management Agency (MEMA) review, the Department of Conservation and Recreation Review, and Massachusetts Department of Environmental Protection Chapter 91 Waterways License. There are many other certifications, notices of intent, permits and reviews that may be involved, these are just a few of the common requirements for a permitting strategy. Following the alternatives analysis, the three design options detailed by the team are discussed in greater detail in “5.0 Recommendations”.

5.0 Recommendations

Within this chapter, the team first reviews other areas of concern in East Boston where significant flooding will occur based on the higher SLR projections created by the team. Next, the team details how the location of Condor Street was chosen for the investigation of a flood protection system. Previously the team modified CRB's 36" 1% annual flood event GIS layer to represent an additional foot of SLR. This new flood map was considered with the current and planned flood protection projects of the City of Boston. Following this investigation, the team chose a project site location with no planned project to fulfill the design component requirement of the MQP. The location of this flood protection system was determined using Social Vulnerability Index (SVI) data, information about future Boston projects, depth grids and the opportunity to inform GreenRoots, a local environmental protection organization. Previously in the Results section "4.3.4 Design Options for Coastal Resiliency," the team provides an alternatives analysis of the different design options for each flood pathway. The team considered different project elements such as the longevity of the design, the cost, permitting level, and operation and maintenance levels. For further information regarding these considerations for the design component location and design option selection, see the methodology found in section "3.3 East Boston Condor Street Coastal Resiliency Design." The team recommends three flood protection designs, one in each of the three flood pathways along Condor Street based on the alternatives analysis findings.

5.1 Other Areas of Flooding Concern in East Boston

As seen in the East Boston SVI maps, almost the entirety of the residential area, excluding Logan Airport, has the highest social vulnerability ranking. East Boston will experience some of the most severe flooding out of the whole city of Boston due to SLR. Another potential foot of SLR by 2070 means deeper and more extensive flooding in more areas than just Condor Street. CRB outlines plans for the majority of the western coast of East Boston; however, CRB marks a large part of the northern and southern/inland shores as future study areas. Many of the plans outlined in Section 4.3.3 and most likely other planned projects in Boston have insufficient design flood elevations (DFE) based on the new projection. According to the Boston Public Works Department Climate Resiliency Design Standards and Guidelines, the DFE for any project protecting critical assets should be 21.5 feet above the Boston City Base, which is the same as 14 feet in the NAVD88 vertical datum. This will be too low if the new SLR projections are true; DFE should be raised at least one foot higher in order to have at least one foot of freeboard. If emissions rates continue in the direction they have been going, projections for 2070 may soon exceed 48" of SLR and require an even higher DFE. This is the continuous struggle associated with designing for a future that is very uncertain. Regardless, with the amount of time and money spent on planning for flood protection, projects need to be adaptable to accommodate for potentially more extreme SLR projections.

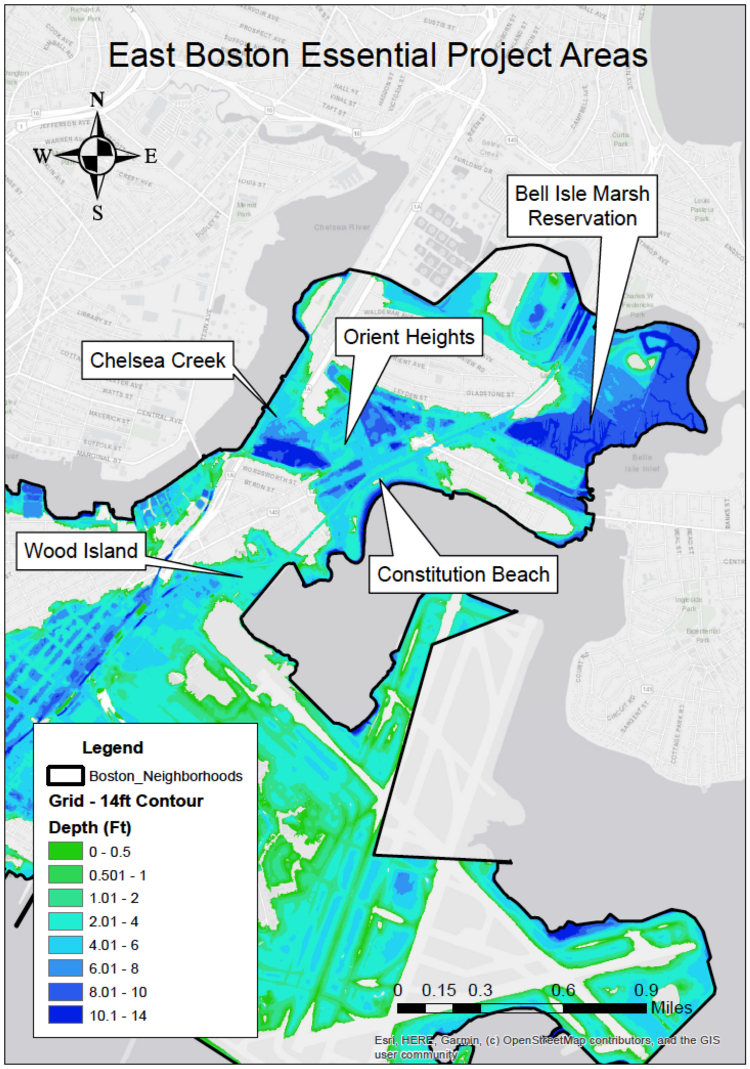

Figure 38. Essential Project Areas in East Boston

Given these considerations, there are a number of areas in East Boston that require more attention than "Future Study Area", as seen in Figure 38. In CRB's Flood Protections Appendix, there is recognition that the Wood Island and Orient Heights areas will be significant flood pathways leading to extensive residential and commercial damage in East Boston. Before the neighborhood was infilled, these two areas were part of the ocean, which is why they stand at such low elevations today. Constitution Beach is an important public amenity. Natural solutions which combine accessibility and functionality with adequate protections are essential along Constitution Beach. To prevent the level of damage made evident by the team's flood depth grid of 48" of SLR will require connecting high points along Constitution Beach as well as Chelsea Creek to the north.

Furthermore, an important flood entry point nearing 2070 will be the bay area east of the Wood Island T Station, which abuts Logan Airport to the north (3). It will be important to collaborate with the Massachusetts Port Authority (Massport) on effective protections, as failure to fortify this area owned by one entity could result in detrimental consequences for hundreds of residents and businesses.

Finally, the northernmost area of East Boston will also be exposed to extreme flooding, notably inland from the Belle Isle Marsh Reservation (4). Although the natural marsh will provide some protection from tidal surges and wave action, rising sea levels and extreme precipitation will cause a large part of the Suffolk Downs area to be inundated. Given a 1% chance storm event, this area would serve as a flood entry point and cause greater flood depths in the Constitution Beach neighborhood.

5.2 Flood Protection Design

After identifying areas within East Boston with no planned flood protections, high levels of flooding, and social vulnerability, the team selected one of the locations to design conceptual project models. The team selected the area of Condor Street close to East Boston's Urban Wild Park as the site for these conceptual project designs. This area has a high SVI ranking and even more flooding due to the increase in SLR. A map of the flood depth in the chosen area is shown below in Figure 39. This coastal stretch of land is experiencing gradual erosion due to increased rainfall, sea level rise, and tidal surges. Land erosion on this parcel now exposes buried waste including old bricks and construction materials. This environmental hazard emphasizes the need for attention and solutions for coastal resiliency. With the projected 48" SLR, the length of street beyond the first most western entrance of Urban Wild would be completely flooded. Additionally, pooling is expected on the most eastern side of the map in the location of the planned construction of an Eversource electric substation. The flooding is expected to inundate more than twenty buildings within the neighborhood, a mix of both commercial and residential.

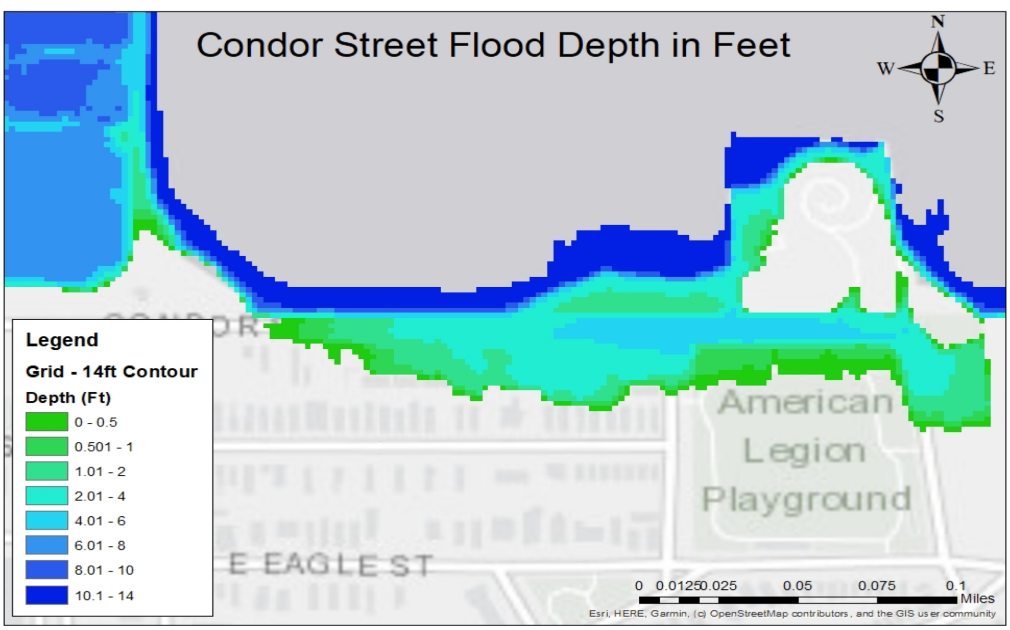

Figure 39. Depth Grid of Flooding during a 1% Chance Flood Event Along Condor Street

The team performed a site visit to the potential project location to gather photos and to gain a better spatial understanding of the area. While on the site visit to Condor Street, the team identified and evaluated the three largest flood pathways. These three areas should be redesigned together to protect Condor Street from future flooding. Within Figure 40 they have been numbered 1, 2, and 3. The alternatives analysis of the three locations informed the decision process for the team's final flood protection design recommendations. The methodology behind the design option weighting and ranking at Locations 1, 2, and 3 can be found in the Methodology in section '3.3.4 Design Options Alternatives Analysis'. Additionally, the design options that the team considered are further detailed, weighted and ranked within the Results in section '4.3.4 Design Options for Coastal Resiliency'. Below are the flood protection design recommendations for Condor Street determined by the team. Given the technicality and feasibility of construction, a consultation with a coastal engineer should be pursued for site-specific solutions.

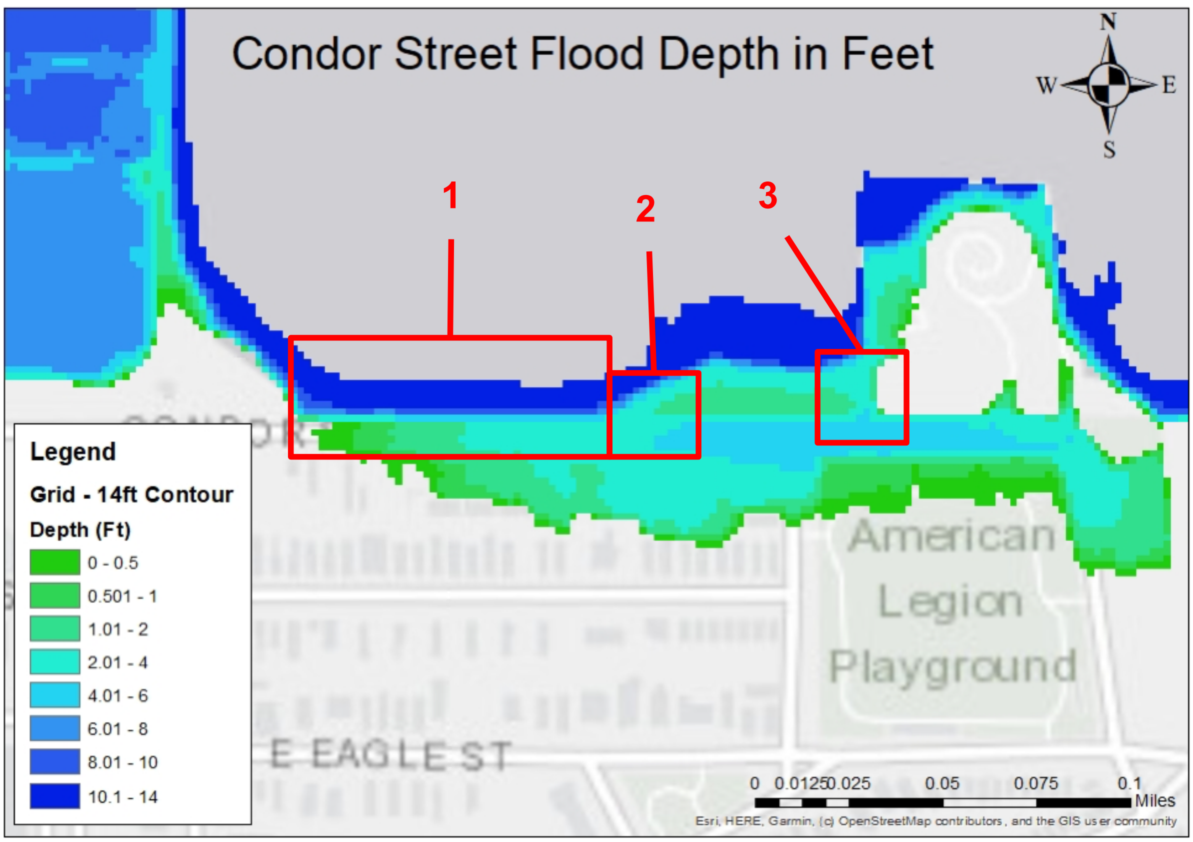

Figure 40. Project Recommendation Locations

<u>5.2.1 Location 1: Replace Existing Wall with Optional Path Expansion</u>

The first design recommendation in Location 1 is the reconstruction of the existing 550' coastal retaining wall along Condor Street with an optional path along a rock revetment in front of the wall. A rendering of this design recommendation is seen below in Figure 41 and a cross-sectional CAD drawing of the wall and walkway can be seen in Figure 42. Sections of the wall along Condor Street have fallen into disrepair and will have to be repaired or entirely replaced at some point in the future. When designing a shoreline structure, sufficient field tests on coastal conditions must be conducted. These conditions including wave activity, tide, currents, wind, and storm surge can significantly impact structural integrity (Massachusetts Coastal Zone Management, 2018). Based on the observations made by the team during the site visit, it does not seem that the wall experiences significant wave action at high tide. Despite this, as sea levels continue to rise, the wall will eventually need to be structurally stable enough to keep out water and prevent the neighborhood from flooding during a storm event. Based on the team's site visit observations, the wall will continue to crumble in years to come due to the erosion of the wall's footing. Currently, the exposed roots of various trees and plants cling to the weathering soils. Repairing or replacing the wall will ensure it is strong enough to weather sea level rise and severe storm events associated with climate change. Ultimately, the wall should be replaced due to the hazard it presents in the event of a total collapse.

Figure 41. Rendering of Replaced Wall, Rock Revetment & Extended Urban Wild Walkway

[Link to before/after visualization]

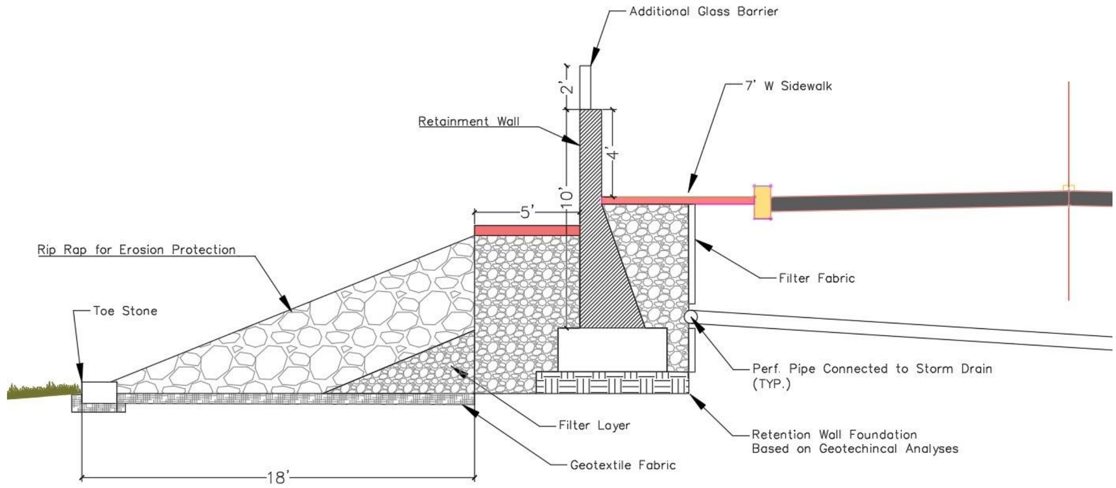

Figure 42. CAD Drawing - Replaced Wall, Rock Revetment, Extended Urban Wild Walkway

Walls along coasts should ideally always be placed tightly against the shoreline. This is commonly referred to as placement landward. This is necessary to prevent loss of beach area and lessen the extent of interaction with tides and waves (Massachusetts Coastal Zone Management, 2018). In some cases, however, permitting agencies understand the complicated nature of coastal flood protection measures, and will evaluate the need to build seaward on a case-by-case basis. This determination should be made in conjunction with an experienced structural engineer, to understand whether or not the current concrete structure can support the loads it will experience in the coming decades as a result of flooding. Regardless of this determination, the end result should be a sturdy concrete structure that incorporates possibilities such as pedestrian seating landward, a pedestrian handrail, and/or a decorative sea glass mural. The handrail would make installation of glass barriers possible, to offer greater protection against flooding but allow for pedestrians to maintain view of the water. These three options offer functional or aesthetic amenities while also protecting residents from flooding due to SLR. Funding, decision making, and construction will be dependent upon the interests of the community and budget restrictions. Any proposed construction extending seaward will be limited.

A typical design solution to dissipate wave energy and prevent the escalation of shoreline erosion is the use of a rock revetment. The team strongly recommends that the wall should be reconstructed with a rock revetment at its base along the coast to prevent erosion and provide an extension of the Urban Wild walking path. The crumbling wall should be built to 4’ at street level. In addition to this 4’ wall, a 2’ glass barrier can be installed along the wall for additional protection for the projected event of larger SLR by 2070. This glass barrier will allow for waterfront views, and a staged construction of the wall.

The current minimum design flood elevation (DFE) for a 2070 1% annual flood event in East Boston is 21.5’ for critical assets according to the Climate Resilient Design Standards and Guidelines for Protection of Public Rights-of-Way by the Public Works Department of Boston (BPWD) (Boston Public Works Department, 2018). Critical assets include structures that protect public-right-of-way such as the wall along Condor Street protecting a sidewalk and roadway. This DFE is based on the Boston City Base (BCB) Datum. This was converted to the NAVD88 elevations used in the team's GIS maps by subtracting 6.46'. Roughly this comes out to have a necessary DFE of 15'. The NAVD88 elevation of the sidewalk along the wall is 11', therefore the height of the wall should be 4'. The extension of the height of the wall with 2' of glass barriers was added to account for an additional foot of SLR and an additional foot for headboard. A required FEMA headboard of 2' is already included in BPWD's 1% annual flood event 2070 DFE to compensate for hydraulic factors such as bridge openings, urban watershed changes and wave action that can increase flood plains (FEMA Glossary, 2020). However, due to the ease of adding a 2' glass barrier in place of a 1' glass barrier, the team deemed it a valuable design addition to protect from SLR.

There are currently rock revetments along Urban Wild. The design of the replacement wall and sidewalk should follow similar design standards of the Climate Resilient Design Standards and Guidelines for Protection of Public Rights-of-Way by the BPWD. Based on the BPWD's sample standards of a raised roadway, the sections of crumbling coastline should be filled in with compacted fill. A geotextile fabric should be placed between the existing ground and compacted fill. The grade of the fill should be determined by geotechnical analyses. The slope of the rock revetment should follow a 3:1 slope and the retention wall should have a foundation designed based on geotechnical analyses. The sidewalk should remain 7' wide and additional flow-through planters can be placed intermittently along the sidewalk. These optional 2' wide plantings lining the roadway will allow runoff to seep through their soils and filter in an underdrain system, gravity fed to an existing lower outfall located along the coast of Urban Wild that is connected to current drainage structures.

The beach area is also littered with broken glass, as seen in Figure 43. The team sees this as an opportunity to create a glass mosaic along one section of the newly constructed wall to involve the community and younger generations in the improvement of the area. A site evaluation must also be conducted prior to construction. During the evaluation, there should be consideration of controlling overland runoff erosion, beach access during construction, the protection of native vegetation, potential impacts on wildlife, and heavy equipment use. Construction of the wall should be completed in a phased manner.

Figure 43. Found Glass on Condor Street Site Visit & Sample Sea Glass Mosaic Wall

5.2.2 Location 2 and 3 Deployable Floodwall at Park Entrance

The next design recommendation is the addition of a deployable floodwall for Location 2 and Location 3. Based on the alternatives analysis for both locations, the addition of a deployable floodwall was the best option. In the event of a storm, the wall would be assembled as a temporary protection measure against storm surges. Flood barriers are most commonly used in areas where a narrow flood pathway needs to be blocked or where more permanent solutions are limited by space, cost, or existing infrastructure.

For Location 2, the floodwall will go at the entrance on the corner of the Condor Street wall and Urban Wild. As seen in the project location map and depth grid, this area serves as an entry point for water during a flood event. The temporary deployable floodwall will extend from the replaced wall to the adjacent vegetated berm. The current vegetated berm will need to be raised 1-2 feet in order to provide a sealed protection from flooding. The current berm appears to be 3-4 feet in height along the roadway. In the case that the wall is replaced, and an additional two-foot glass barrier is added to the wall, a deployable floodwall with a height of 6’ will be necessary to continue the same height of protection against flooding along the entrances to Urban Wild. The deployable floodwall scored better in the alternatives analysis compared to the other two options which included adding an elevated pier at the corner of the wall and Urban Wild center or adding fill to create an elevated vegetated berm. The elevated vegetated berm extension that runs to the replaced wall would have blocked ADA accessibility at this entrance to Urban Wild, and the elevated pier is a costly solution.

As shown in Figure 44, to seal this flood pathway, two retention walls on either side of the deployable floodwall should be constructed for ease of installation of the barrier. These walls should have a height of 6’, this will allow for continuation of flood protection at an elevation consistent with the fully expanded 4’ replaced wall with a 2’ glass barrier. The berm behind the wall should be filled in to prevent structural degradation due to water damage. It is necessary that a party is made responsible for the installation of the floodwall before a flooding event. The team recommends community partnerships with local businesses that are most at risk for flooding. For example, there is potential for storage and operation of the floodwall by the Auto Body shop along Condor Street. This is discussed more in section “5.3 Community Outreach and Education.”

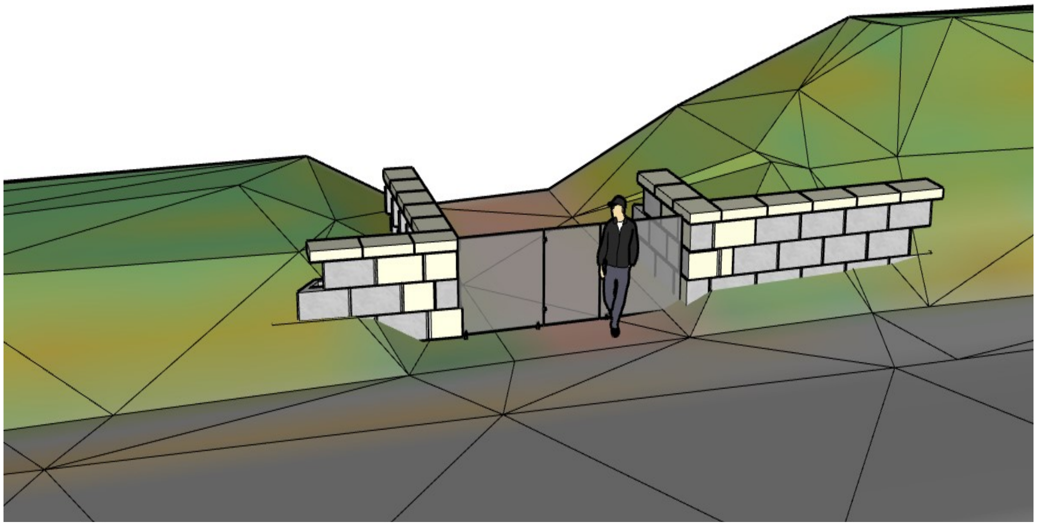

Figure 44. Rendering of Retention Walls

A commonly used product for building protection in the City of Boston is AquaFence (Figure 45). The AquaFence, a FEMA compliant solution, has the highest certification as a flood barrier. It has been approved by the US Army Corps of Engineers and ASFPM (The Association of State Floodplain Management). The fence is code compliant with IBC 2015, ASCE 7-10, and ASCE 24-14. In terms of deployment, 100 linear feet can be set up by a four-person team in one hour. The Boston Department of Public Works Design Standard and Guidelines layout the costs of building a deployable floodwall. The cost is dependent on the width of the area that needs to be blocked and the desired height of the floodwall, which is 6 ft tall. For a floodwall with a 6 ft height, it costs $575 per linear foot. It is expected that the cost of the AquaFence for Location 2, which has a 12-foot width, would be $6,900. Location 3 has a 10-foot width, so the floodwall would cost $5,750. If any additional anchors are needed, it would cost an additional $10 per linear foot. These estimated costs are based on the width of the two park entrances, as measured on Google Earth, so they may not be exact. Furthermore, the barrier can be extended, no heavy equipment is required for installation, it has an easy breakdown, and the fences are stackable 4 high in storage crates. Five of the V1800 (6’) AquaFences assembled together would provide roughly 20’ wide and 6’ high protection (AquaFence, 2020).

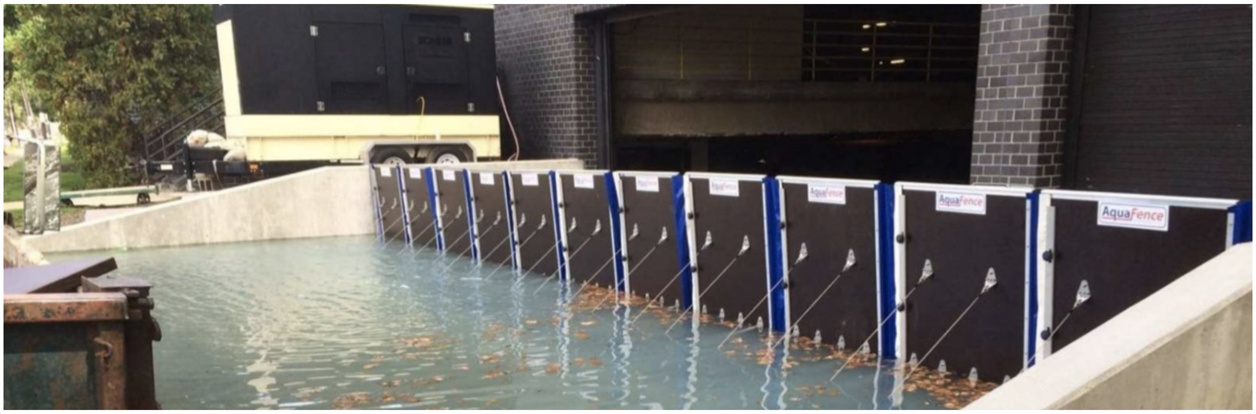

Figure 45. Deployed AquaFences

During the alternatives analysis for Location 3, the deployable floodwall was found to be the best solution. In the case of this Urban Wild entrance, the desire to maintain access to the existing grade influences this recommendation. Raising the walkway with a vegetated berm, for example, would require a new ADA accessible entrance and more extensive construction. The installation of a storm grate system connected to a small wet well and drainage pump was also considered by the team. The storm water for the neighborhood is gravity fed to an outfall along the coast of Urban Wild. Thus, in the event of a flood during high tide this additional drainage system would not be effective. An alternative solution for this would be a new pump and outfall. Connecting to the existing outfall would simply push water into the rest of the drainage area. A small wet well would have to be dug out and a drainage pump would have to be placed in the immediate vicinity. However, there is no power on the Urban Wild side of the street; therefore, a transformer and emergency generator would be required, all of which are extremely costly and an unlikely design solution for a 1% annual flood event.

5.2.3 Living Shoreline Additions

Additional considerations for the coastal area along Condor Street include required remediation work and the addition of living shoreline elements to prevent further coastal erosion and promote wildlife. The property adjacent to the crumbling wall is Urban Wild — East Boston’s first public park along Chelsea Creek (*NOAH - Chelsea Creek Restoration Project*, 2006). Urban Wild underwent significant remediation work, costing $1.2 million, due to high levels of arsenic and lead during the brownfield remediation process in 2003 (Martin, 2020). There is a high likelihood that similar levels could be found at the adjacent site along Condor Street, requiring remediation prior to construction. If remediation of the soil is deemed necessary for construction there is potential for significant costs associated with the clean-up. The full extent of contamination on this site is unknown by the team, but the costs associated with clean-up may be similar to the nearby Urban Wild site. In addition, there is also significant clean-up that should take place along the beach to remove large amounts of trash.

The USACE and NOAA have developed a community practice called SAGE or Systems Approach to Geomorphic Engineering (NOAA Living Shorelines Workgroup, 2015). SAGE provides natural and structural measures for shoreline stabilization. Based on SAGE recommendations for low wave energy environments, vegetation of native grasses allow soil to be held by roots to slow inland water transfer, assist in flood water storage, provide ecosystem service and maintain the aquatic-terrestrial interface. The initial construction can be up to $1000 per linear foot, and up to $100 per linear foot in annual operations and maintenance for a 50-year project life (SAGE, 2015). Native grasses already grow below the rock revetments along Urban Wild. These native grasses can be seen in photos from the site visit completed by the team in Figure 46. The team recommends the incorporation of these native grasses along the coastal mudflat region beyond the rock revetment recommended along the shoreline. The team also recommends the use of Breakwaters. These offshore structures placed in shallow water reduce the forces of waves before they hit the shore, stabilize wetlands, and can function like a reef for marine life. Initial construction is expected to be $2001-$5000 per linear foot dependent on the type of breakwater used and would require over $500 per linear foot in annual operations and maintenance each year (SAGE, 2015). A rock revetment with coastal grasses and rock breakwaters, seen below, are also located along Urban Wild emphasizing the benefit of the continuation of a similar structure along the length of Condor Street.

Figure 46. Current Native Grasses & Breakwaters at Urban Wild

5.3 Community Outreach and Education

Community outreach is a vital consideration for empowering communities to build resilience in light of increasing challenges. As outlined by the BPWD Design Guidelines, ownership and empowerment are necessary aspects to community resilience projects that instill a responsibility to be a part of the plan and a mandate to act (Boston Public Works Department, 2018). Systems such as the deployment of the floodwall by community members further promote ownership and engagement principles, making solutions practical for communities. Additionally, a community resilience initiative recommended by CRB details district-scale adaptation that plans to leverage existing community organizations through a climate resilience committee. This committee can coordinate efforts in line with neighborhood character and growth with different project stakeholders. Future efforts can also include initiatives to conduct outreach campaigns to private facilities serving vulnerable populations to promote engagement with emergency preparedness and adaptation planning.

Figure 47. Exemplary Educational Signage Along the Coast

Community education is a necessary means to promote awareness for current and future flood hazards. This can be performed on many different scales and directed at various groups. One recommendation to educate the general public, including residents within the area, is through educational signage along the coastline, similar to Figure 47. This signage could be added along the wall, or further added around Urban Wild's coastline and walkway. Signage can include the historical context of Boston's bay area infilling during the 17th century, the causes and effects of climate change, future projections of SLR and typical methods of protection initiatives within the city. It can also provide safety measures to follow in the event of significant inundation within the neighborhood.

A second recommendation by the team is to promote a program with local elementary and middle schools to perform a coastal walk field trip with a sponsoring organization such as GreenRoots, an environmental protection organization. School groups could visit the project site, read educational signage and engage in a program that explains the effects of climate change and risks of SLR. A "nature walk" along the coast could provide interactive engagement to promote the visitation of the coastal walkway in the future. A hands-on activity could also be developed to explain coastal erosion. This field trip could alternatively be repurposed in a virtual manner for online schools during COVID-19 using Google Earth and a video meeting platform such as Zoom or Google Meet.

A third recommendation is the promotion of Greenovate, the initiative of Boston's Mayor Marty Walsh to engage the public in eliminating the harmful greenhouse gases causing climate change and to continue to make Boston a healthy, thriving and innovative city. The Greenovate website details different programs such as Carbon Free Boston, Waste Free Boston and Climate Ready Boston. Additionally, the website contains other opportunities to get involved such as volunteer programs, climate preparedness workshops and training. The scale of climate change is so large and so vast; it is essential that residents, business owners, and the leaders of our communities stay well informed and action oriented.

6.0 Conclusion

The team really enjoyed working on this project. Being able to dive into a truly crucial topic for a lengthy and extensive project, such as the MQP, was deeply valuable to all of the team members. Sea level rise and flood protection are remarkably extensive and complicated subjects and the team learned through research and writing the report that there is no right answer and the situation is in constant flux. Considering how relevant climate change is right now and will continue to be, the team feels very fortunate that they had the opportunity to study it so closely.

Climate change is going to continue to get worse and lead to more extreme storm events unless major steps are taken to decrease emission rates. The fact that the City of Boston is actively taking these steps to ensure protection of the City, its residents, and businesses so early on is extremely promising. The sooner actions are taken and the more people, specifically government officials, that get behind climate resiliency, the better the protections will be. The work that Climate Ready Boston is doing is immensely important, but at the same time there is so much more that needs to be done. It is important to use the most up to date and accurate predictions in the City's best interest. That is why doing work like this project is imperative to the continued prosperity of Boston.

All that in mind, however, there is only so much that sea walls and vegetated berms can do at the current state of emissions. After a certain point, flooding and sea level rise could get so bad that cities cannot keep up with the water. Either serious measures need to be taken to stop the impact of climate change now before it is too late, or cities like Boston need to learn to live with water rather than fighting it.

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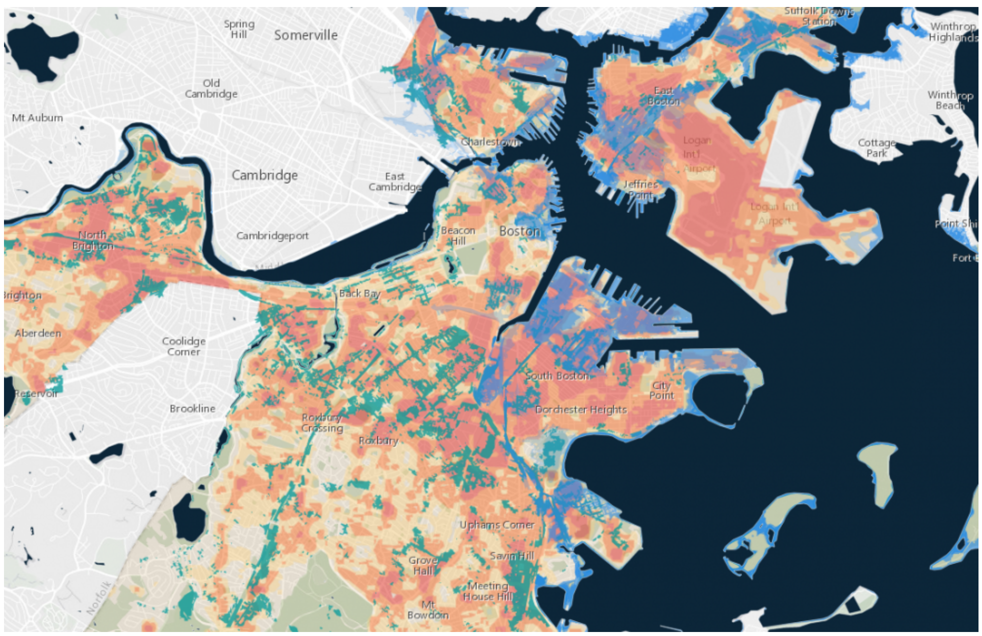
Appendices

Appendix A: Project Proposal

Working Towards Climate Resiliency in Boston, MA



A Major Qualifying Project Proposal Submitted By:

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October 2020

Capstone Design

The Accreditation Board for Engineering and Technology (ABET) requires that all accredited engineering programs complete a capstone design experience before acquiring an engineering degree. Through a capstone design experience, students demonstrate skills and knowledge acquired through their studies and coursework. At Worcester Polytechnic Institute, the capstone design experience is fulfilled through the Major Qualifying Project (MQP).

It is predicted that the City of Boston, MA (the City) will continue to see a rise in sea level in the coming years due to climate change. In 2016, it was predicted that Boston's sea level will rise 36 inches by 2070. However, new predictions show that the sea level rise (SLR) may be 8 inches more than that, totaling 44 inches. Projection maps and SLR mitigation projects were created for the original 36 inches for the City to assess how a rise in sea level will impact its residents and infrastructure. To assess the impact of an additional 8-inch SLR, ArcGIS will be used to determine which areas of the City will be impacted more in 2070 as compared to previous projections. This information will then be used to determine which social groups and communities will face a greater impact. This project will use civil and environmental principles and will address the following real-world constraints:

Economic

Climate change increases sea level, storm surges, extreme heat, and riverine flooding events. These events have damage costs. Property damage, resident relocation, and business effects make up most of the total cost of damage due to impacts of climate change events. The City will have to pay for damages to buildings, stormwater systems, transportation systems and forced relocation of families and residents. Additionally, as a result of flooding, businesses are repeatedly and frequently interrupted, resulting in a loss of revenue and wages. The team's analysis will better prepare Boston for potential climate change events with the use of ArcGIS to prioritize projects that will reduce the costs of the SLR's impact.

Environmental

The main focus of the project is to help Stantec and Boston assess how climate change predictions will impact the City and its neighborhoods. Over the past decade there has been a concerted effort to include climate change responses in the master plans for Boston. The City has begun this process in collaboration with Climate Ready Boston (CRB) to prepare for the projected SLR in 2030, 2050, and 2070. The team will address the environmental impacts of this additional SLR through the application of ArcGIS and an analysis of how planned projects will mitigate these effects.

Ethical

The project will adhere to the American Society of Civil Engineers Code of Ethics. The team will be unbiased in decision making for this project and will, to the best of their ability, provide a thorough analysis of the impact of SLR and how equity is considered in Boston's future flood resiliency projects.

Social and Political

Multiple Census data layers will be used in the analysis to ensure that many different ethnic and income groups are represented in a sensitivity analysis. Vulnerable groups living in Boston will be overlaid where the most damage will be. This will be used to understand the impacts on different social and political demographics.

Health & Safety

Safety concerns will be addressed in the project by assessing how people will be affected by the rise in sea level. Possible safety concerns include water damage to buildings, damage to materials, and water damage that is exacerbated by freezing. These concerns can lead to structural failure resulting in unsafe conditions in residential and commercial buildings. There are also more immediate public health concerns with flooding, such as basement flooding and emergency relocation during a flood event. Boston’s combined storm sewers can overflow during a storm, contaminating flood water with raw sewage which poses a major risk to the public’s health. Depending on the extremity of a flood event, emergency relocation of citizens can be dangerous and present safety risks. Measures to decrease these impacts will be ranked based on their cost-benefit analysis. While this project will not directly address the impact climate change has on people’s mental health, repercussions such as chronic stresses from extreme heat, mental strain from property damage or displacement, and higher levels of stress or anxiety after a disaster will be considered throughout the engineering process.

Table of Contents

Key Terms and Abbreviations

BCA - Benefit-Cost Analysis
BRAG - Boston Research Advisory Group
BSWC - Boston Sewer and Water Commission
CRB - Climate Ready Boston
FEMA - Federal Emergency Management Agency
GIS - Geographical Information Systems
MHI - Median Home Income
Polygon - A feature type in the form of a shape with three or more sides used to depict spatial data in ArcGIS
Sensitivity - The degree to which groups of residents are disproportionately affected by emergency situations and climate change effects
Shapefile - A format used for geospatial vector data storage and organization in ArcGIS
SLR - Sea Level Rise
Vulnerability - Refers to social groups that are more at risk during emergency situations due to their level of exposure to the associated hazards of the situation

1.0 Introduction

In 2016 the City of Boston launched an initiative called Climate Ready Boston (CRB) to better understand and prepare for the impacts of climate change on the region. Preparing and understanding future climate risks can help deter future damages and costs to the City and its people. One outcome of the initiative was a detailed exposure and consequence analysis of the cost to the City of future climate change scenarios. The three climate-related hazards CRB focused on were chronic stresses of extreme heat, impacts from stormwater flooding, and coastal and riverine flooding events. CRB specifically looked at how 36 inches of SLR by 2070 would affect the City. Since this study, new reports have revealed that SLR is anticipated to be 8 inches higher by 2070 (44") than the 2016 prediction (36").

This project team's goal, with the support of Stantec Inc, is to understand how this new prediction will affect the City and its respective neighborhoods. The team developed four objectives: replicate this study with the higher 44" SLR scenario, conduct a cost-benefit analysis considering new affected areas and proposed projects, identify vulnerable populations throughout the City by conducting a sensitivity analysis, and design a project that will protect these vulnerable populations from the additional SLR. The results of a new analysis will provide updated guidance to Stantec, and subsequently the City, on how to best prepare for the extreme environmental changes that will be seen in the future.

2.0 Background

The following sections provide the framework on which this project is informed. It is crucial to understand the what and why of a project before developing the how. The group will discuss Stantec as a company and how they are connected to CRB, the history and demographics of the City, and how CRB performed the analysis that will be replicated.

2.1 Stantec

Stantec Inc. is a design and consulting engineering firm with 22,000 employees and 350 offices worldwide (Stantec, 2020a). The company was started by environmental engineer Dr. Don Stanley in Edmonton, Canada in 1954 (Stantec, 2020b). Sixty-three years later, Stantec was ranked number ten by *Engineering News-Record* on the "Top 150 Global Design Firms" list and number nine on the "Top 300 Architecture Firms" list by Architectural Record (Stantec, 2018). In 2019, Stantec had a revenue of over 926 million dollars. Stantec states that all of their projects are designed with a focus on the community (Stantec, 2020c). Their services include buildings engineering, client enterprise solutions, community development, environment, landscape architecture, sustainability, and water services.

Stantec has worked on projects with SLR and climate change resilience in the past. This work has been done for the Boston Sewer and Water Commission (BSWC) and also in Somerville and Cambridge, Massachusetts. Stantec created models for flood projections in Cambridge (D. Vanhoven & S. Harrison, personal communication, October 2, 2020). In Somerville, Stantec created a Climate Change Vulnerability Assessment to help understand how climate change will impact the City. This assessment, along with outreach and engagement, can be used by Somerville to determine a plan to mitigate those actions (Stantec, 2017).

2.2 History of Boston's Development

The landscape of Boston was forever changed during the Industrial Revolution when hills were excavated and used to fill in the bay area. During the 17th century, Boston nearly doubled in size due to these infills (Whitehill, 2000). Boston has been traditionally protected from storm surges and waves by the Harbor Islands, which have created a false sense of security (Sasaki, 2016). The City was built only a few feet above the water. Thus, today the City experiences high tides known as "king tides." Boston has also been recently impacted by various storm surges such as Hurricane Sandy in 2012 and Winter Storm Grayson in 2018, which caused the high tide to hit 15.1 ft, a similar record to the Great Hurricane of 1938 (Boston Discovery, 2020). Climate change has started causing Boston's coastline to return to its pre-industrial landscape with SLR, meaning sea level elevation is starting to negate the raised elevation the infills provided. Storms are also becoming more frequent and more destructive due to climate change (City of Boston, 2016). It is important to note that Boston's drainage infrastructure is composed of 670 miles of storm drain and 155 miles of combined sewer lines (BWSC, 2020). While the City is in the process of replacing combined lines, the existing ones can overflow, putting the public's health in danger of exposure to sewage water during flooding.

2.3 Climate Ready Boston

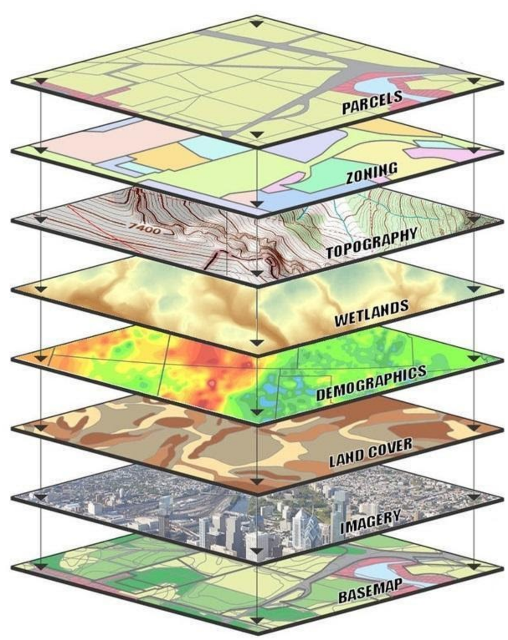
CRB is an "initiative to get the City ready for the long-term impacts of climate change" (City of Boston). The project was started in November 2015, and CRB's official report was released on December 6, 2016. There are four sections of CRB: Updated climate projections, vulnerability assessments of climate change hazards, focus areas, and climate resilience initiatives. Climate scientists from the University of Massachusetts Boston, known as the Boston Research Advisory Group (BRAG), developed the climate change projections. CRB's updated climate projections incorporate three different hazards of climate change: extreme temperatures, storm water flooding, and coastal and riverine flooding. The City of Boston recognizes the importance of preparing for the effects of climate change and appointed CRB to identify the associated costs. To evaluate the cost of climate change to the City, the project considered the cost of infrastructure damage, property damage, resident displacement, business disruption, and more. After calculating the cost of damages throughout the City, CRB identified key climate resiliency initiatives that would help prevent this damage. Some of these projects involve educating residents on the impact of climate change and how they can help slow the effects by changing some of their own habits, adapting buildings and improving infrastructure.

Major findings from the 2016 CRB report indicate that by the late century, even without storm surges, 5% of the City will be flooded. Without any projects that prevent damage caused by sea-level rise, by 2030s-2050s flooding from 1% annual chance storms will cost $2.3 billion in damages. These events will flood 2,100 buildings, impacting 1,600 residents. That number is expected to rise to 11,000 structures and 85,000 residents by the 2070s. An important takeaway of CRB is the compounding threat of flooding and storm surges in the future. An annual 1% flood event in 2030-2050 will become a monthly flooding event in 2070 (City of Boston, 2016). CRB wrote a supplementary appendix detailing how these calculations and analyses were obtained, both through spatial analysis software and the Federal Emergency Management Agency (FEMA) flood-model estimation methodologies.

2.4 Benefit-Cost Analysis

CRB used Geographic Information Systems (GIS) software called ArcGIS by Esri to perform exposure and consequence analyses for twelve different inundation scenarios. GIS is a powerful tool used for spatial analysis of both geographic and social/demographic data originating from many different sources. GIS makes it possible to recognize new relationships and characteristics between combined datasets, which in turn strengthens new predictions and decisions.

In order to understand the impact of a certain flooding scenario, CRB manipulated data through overlay and analysis tools detailed in their report (Figure 1). By pulling data from reputable sources like MassGIS, BostonMaps, and MassDOT among others, CRB aggregated and cross-checked data to create an accurate replication of the City of Boston's infrastructure and demographics. They modeled and analyzed three sea-level rise (SLR) scenarios: 9", 21", and 36", with each divided further into four different coastal flooding scenarios: 10%, 2%, 1%, and 0.1% annual chance events (also commonly known as, respectively: 10-year, 50-year, 100-year, and 1,000-year floods). Accounting for stormwater flooding with a ten-year, 24-hour rain event, the analysis totaled twelve flood scenarios accounting for both coastal and riverine flooding. After completing data aggregation and manipulation, CRB was able to further assess



inundation impacts at infrastructural and social levels. They used FEMA's Multi-Hazard Loss Estimation Methodology manual, deriving specific damage and relocation costs/loss estimates from parameters outlined by FEMA through extensive national datasets and technologies.

Climate projections since the release of the 2016 CRB report have predicted a greater sea-level rise by 2070 of 44" as opposed to the previous 36" SLR prediction. This is a result of more extreme climate change models: assumptions and projections are now higher due to human activity. SLR and subsequent storm surges will undoubtedly have larger impacts on infrastructure, businesses, and residents than the initial exposure and consequence analysis.

The focus areas CRB defined in their report are Charlestown, Charles River, Dorchester, Downtown, East Boston, Roxbury, South Boston, and South End. The vulnerability assessment CRB completed concludes that there are four concentrated areas of the City that will be impacted more severely than others by inundation in the near future. These neighborhoods of major concern are South Boston, Downtown, East Boston, and Charlestown. When the report was released in 2016, planning initiatives for climate resiliency were first focused on Charlestown and East Boston. The South End is also a concern, but not until later in the century. Areas such as the Seaport and East Boston have been recently developed, and are also under threat of inundation. This recent investment presents an opportunity to leverage action from developers for the resiliency of these areas.

The threat of inundation also presents a unique opportunity to design infrastructure that prevents damages due to SLR while simultaneously improving the City's amenities. This is commonly described as a project's "additionality." While gray infrastructure such as floodwalls present short-term prevention of damage, these solutions can be costly due to their limited functionality. Projects like levees, designed to be recreational trails and parks, that also function as hold space for water take an innovative approach increasing the benefit of the project for the City.

2.5 City of Boston Demographics

CRB provided spatial maps of several socially vulnerable groups: older adults, children, people of color, people with limited english proficiency, people with low-to-no-income, people with medical illnesses and cases of medical illnesses. However, other than an infographic outlining census areas of low to no income households that will be impacted by 36" SLR, there are no considerations of how to prioritize projects to ensure socially equitable resilience in the future. CRB's Strategy 5, found in the Climate Resiliency Initiatives describes Initiative 5-2 of Creating a Coastal Protection System as determining a consistent evaluation framework for flood protection prioritization. The report says: "It is critical to consistently quantify the social, environmental, and economic benefits of each alternative intervention—with particular attention to social equity and the needs of socially vulnerable populations—so that they can be weighed both against the costs of the project and against each other. Any evaluation framework must compare a baseline "without project" scenario, in which flood risk continues to increase with SLR, to "with project" scenarios, in which flood risk is managed through appropriate interventions" (City of Boston, 2016).

It is important to consider socially vulnerable populations when looking at the impact of climate change on the City of Boston. Increasing SLR poses significant threats for public health and socially vulnerable groups which are identified on the basis of age, income, racial distribution, homelessness, disabilities, and language barriers. Older residents are more likely to have preexisting health conditions or develop health problems over time. In emergency situations, it's important to consider how these vulnerabilities impact a community. Income can play a large role in emergency situations — the cost of displacement and paying out-of-pocket would have a larger impact on lower-income residents. Similarly, persons who are homeless may have a harder time relocating. Mobility and the ability to relocate quickly is an important factor to consider with emergency planning. Persons with disabilities or medical illnesses may have a harder time, and the cost of displacement can be very expensive if persons need additional support. Additionally, in Massachusetts, the city with the highest immigrant population is Boston, making it home to many different languages (*New Bostonians Demographic Report*, 2005). Emergency announcements are not as accessible to those whose first language isn't English. A final social vulnerability the team will be looking at is racial and minority distribution. Historically, minority communities have lower incomes and less wealth which makes financial recovery from the effects of climate change more difficult. The following data on the City of Boston was taken from the U.S. Census Bureau (United States Census Bureau, 2019).

2.5.1 Age Distribution

Estimates of the population age were obtained to interpret and understand social and economic characteristics. The data is used to plan and analyze policies and programs along with other population characteristics. This data was produced for the United States, along with the Commonwealth of Puerto Rico.

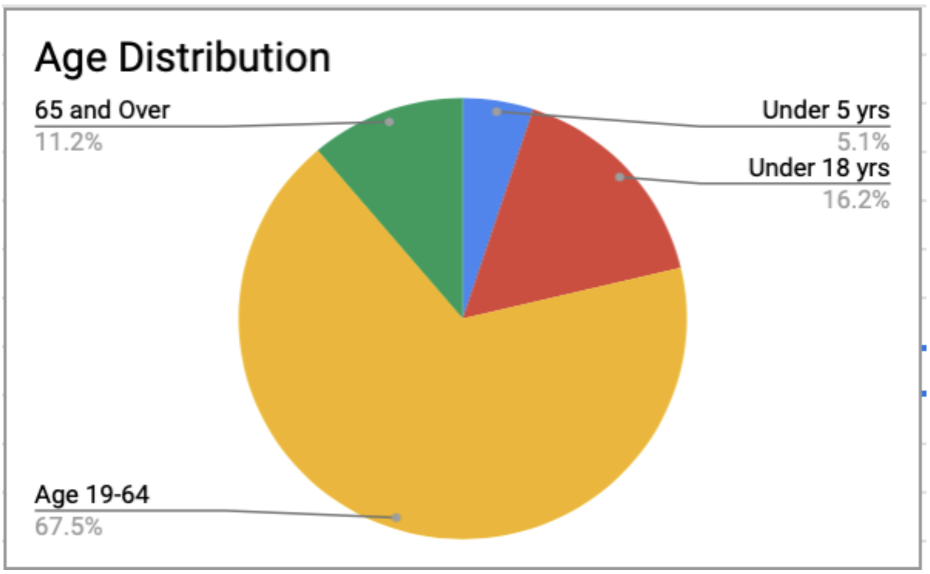


Figure 2: City of Boston Age Distribution

2.5.2 Race and Hispanic Origin

Race estimates of the population are produced for the United States and the Commonwealth of Puerto Rico. Data is based on self-identification. Self-identifiers for race generally reflect a social definition recognized in the country, and not an attempt to define race for any other reason including biologically or genetically. The groups include national origin along with sociocultural groups. Since the data is based on self-identification, people may choose to report more than one race they identify with.

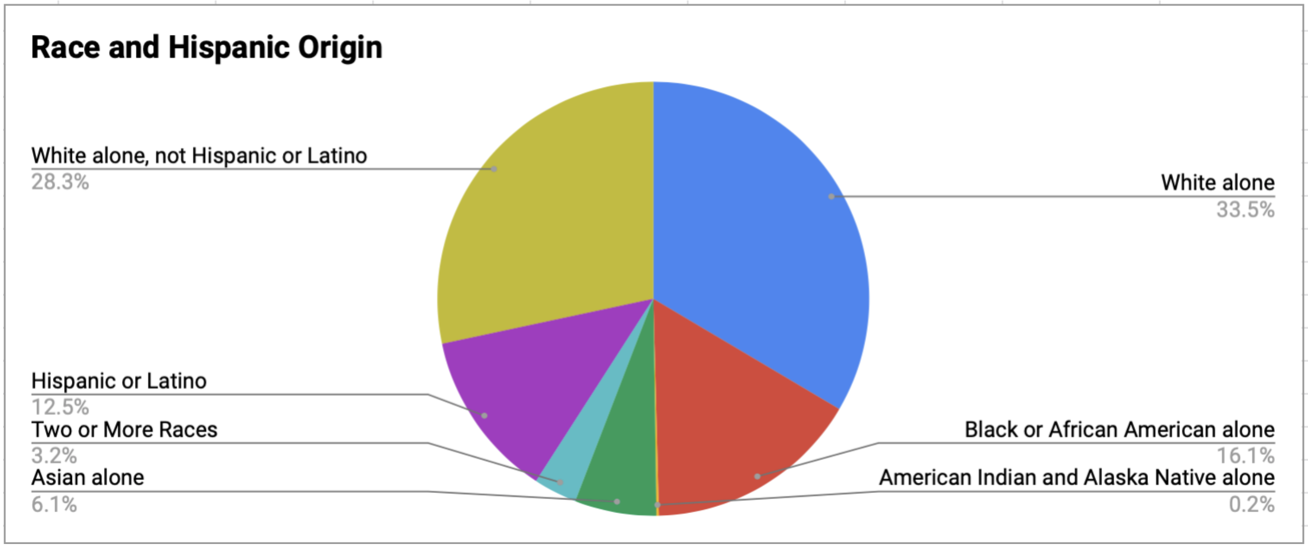


Figure 3: Race and Hispanic Origin statistics

2.5.3 Population Characteristics (2014 - 2018)

Veterans are persons who have served but are not currently serving in the military. The data is restricted to people who are 18 years and older. This information was collected in the American Community Survey and the Census Bureau.

Foreign-born persons include anyone who was not a U.S. citizen or a U.S. national at birth, however the data also encompasses respondents who are a U.S. citizen by naturalization or who are not currently a U.S. citizen.

Table 1: Population Characteristic statistics

Veterans (persons)	16,547
Foreign born persons	28.5%

2.5.4 Families & Living Arrangements (2014-2018)

A household includes all persons who occupy a housing unit — which includes a house, apartment, mobile home, group of rooms, or a single room, as their place of residence. Single rooms with separate living quarters include those that have direct access from outside the building or through a common hall. The number of people residing in households is not considered in this number.

Persons per household (average household size), is found by dividing the number of persons in each household, by the number of households.

Living in the same house for the past year is evaluated in partnership with the location of current residence to determine the extent of residential mobility of the population along with their redistribution.

For languages other than English spoken at home, persons reported whether they sometimes or always spoke a language other than English at home. Those who knew other languages but did not use them at home were excluded from this data.

Table 2: Family and living arrangement statistics

Households	266,724
Persons per household	2.37
Living in the same house 1 year ago, percent of persons age 1 year+	79.9%
Language other than English spoken at home, percent of persons age 5 years+	38.0%

2.5.5 Health (2014 - 2018)

The Census Bureau and American Community Survey include a variety of characteristics to define 'disability'. These characteristics include hearing, vision, cognition, ambulation, self-care, and independent living. Activities like bathing, dressing, ability to run errands such as shopping were also taken into consideration. These characteristics and factors are used to create a disability measure, or independently to identify populations with specific disabilities.

Table 3: Health statistics

With a disability, under age 65 years	8.6%
Persons without health insurance, under age 65 years	4.2%

2.5.6 Income & Poverty (2014 - 2018)

Median household income includes the past 12 months along with the income of those in the household who are 15 years and older, whether they are related or not. Many households only consist of one person, so the average household income is usually less than the average family income. The data also includes households with no income in the past 12 months.

Per capita income is the mean income computed for every person in a specific group, including those who live in group quarters. It is measured over the past 12 months and is found by dividing the aggregate income of the group by the total population.

For persons in poverty, the Census Bureau uses a set income baseline that varies with family size to determine who is in poverty. If the family's total income is less than the family's baseline, then that entire family is considered in poverty. The official poverty definition does not include the use of non-cash benefits such as Medicaid, public housing, and food stamps.

Table 4: Income and poverty statistics

Median household income (2018)	$65,883
Per capita income in the past 12 months (2018)	$42,010
Persons in poverty	20.2%

2.5.7 Geography

Persons per square mile and land area measurement data includes both land area and water area, which includes inland, coastal, and territorial seawater. For persons per square mile, population and housing density are calculated by dividing the total population or number of housing units.

Table 5: Geography statistics

Population per square mile (2010)	12,792.7
Land area in square miles (2010)	48.28

2.6 Equity in Emergency Planning

Studies from around the world repeatedly demonstrate that minorities are disproportionately affected by climate change. People of color, people with low income, and other minorities tend to live in areas with less elevation and with poorer quality housing. As a result, these people are affected more by the damages and repercussions of coastal flooding and storm surges. For example, people with lower income often have most of their wealth embedded in their property, while individuals with high income have a wider array of assets. This makes recovery from a total loss of property damage in a flood significantly harder for someone who does not have the financial resources to replace their belongings. Further, even the cost of temporary displacement due to unsafe conditions as part of a flood has a significantly higher impact on a person with low income. Not only are the effects of flooding and storm surge events felt more by low-income and minority people, they are also likely to happen more often and severely in densely populated, low-lying urban areas commonly composed of vulnerable communities. These areas tend to also have less green space to absorb runoff (Reckien et al., 2017).

Several cities throughout the United States are beginning to consider equity in planning for climate change and its associated disaster events. Many attribute the shift to equity-based planning to the FEMA response to Hurricane Katrina's effects on New Orleans. Large neighborhoods in New Orleans are home to many minority and low-income groups. These people were not prepared for the storm and lacked access to funds and resources to relocate and eventually rebuild afterwards (Pierre & Stephenson, 2008). Some cities, like Portland, Oregon, have created an Office of Equity and Human Rights to "promote equity and reduce disparities based on race and disability within City government as its primary task" (Portland Office of Equity and Human Rights, 2020). Massachusetts has implemented a Municipal Vulnerability Preparedness Program (MVP) that helps towns plan for climate change and encourages consideration of social issues through the process (Municipal Vulnerability Program, 2020). It is essential to dive deeper into the social and economic aspects of climate change as the City works to prepare for its effects. Considering social and economic factors in this planning allows the City to better protect its most vulnerable populations that often feel the effects of climate change more acutely than others.

3.0 Methodology

The overarching goal for this project is to help Stantec and the City of Boston assess how new climate change predictions will impact the City and its respective neighborhoods. The team developed four objectives to help us meet this goal:

- Objective 1 - Model the 36" and 44" SLR predictions with and without planned projects using similar methods to the initial CRB analysis;
- Objective 2- Use the 44" SLR model to calculate property damage, resident displacement, and business damages costs;
- Objective 3- Conduct a sensitivity analysis of vulnerable populations throughout the City to identify areas of greatest concern in regards to SLR impact;
- Objective 4- Design a conceptual model for a project within a vulnerable neighborhood not met by the planned Boston projects.*

*This objective is subject to change due to the limited timeframe of the project.

The following sections describe the methods that will be used to meet the goal and objectives.

3.1 GIS Mapping SLR with 36" and 44" Scenarios

Initial analysis of an additional eight inches of SLR will require collecting numerous datasets, layers, and shapefiles in order to perform overlays and analyses in ArcGIS. The team will use the CRB Approach and Methodology appendix as a reference for which data sources should be used and how the data can be manipulated. Time and manpower constraints will prevent as comprehensive an analysis as CRB's; the report combined sets of the same data from multiple sources (i.e. building footprints compiled by MassGIS and the City of Boston) to create one master set of data that is as accurate as possible. For this project, the team will only use one source for each type of data such as MassGIS, BostonMaps, Analyze Boston, or MassDOT rather than aggregating the same data from more than one source.

Using the layer from Analyze Boston titled "36inch Sea Level Rise 10pct Annual Flood" will allow the team to replicate the most hazardous impacts to the City, as more frequent storms (10% as opposed to 1%) are forecasted to be a greater financial burden (Green Ribbon Commission, 2016). The group will combine this layer with topographic data and use the "Intersect" geoprocessing tool in ArcGIS to model inundation at the new projection of 44" of SLR. The 44" SLR polygon will envelop those elevations previously 8" above the 36" limit of inundation. The CRB Appendix contains a complete list of all the layers they used to perform an exposure and consequence analysis. The team will include all layers that contain the data on asset values needed to perform calculations of property damage, resident relocation, and business damage costs. These layers include topography, roads, building footprints, hydrography, assessors parcels, and census tracts, to name a few.

3.2 Assessing Damage Costs due to Sea Level Rise

After a new GIS map has been created, the team will identify areas that will be newly affected or more affected by the 44-inch rise compared to the 36-inch rise. Costs of property damage will be determined using building replacement values (BRVs) and contents replacement values (CRVs) calculated by CRB (Figure 4) based on:

- FEMA's Multi-Hazard Loss Estimation Methodology (Hazus)
- RSMeans Building Construction Cost Data
- US Army Corps of Engineers (USACE) Studies

Hazus	Occupancy Code	BRV	CSRV	CRV
RES1	Single Family Dwelling	$143.14	0.69	$98.77
RES2	Mobile Home	$137.47	1.14	$156.71
RES3A	Multi Family Dwelling - Duplex	$117.76	0.69	$81.25
RES3B	Multi Family Dwelling – 3-4 Units	$227.31	0.69	$156.85
RES3C	Multi Family Dwelling – 5-9 Units	$227.31	0.69	$156.85
RES3D	Multi Family Dwelling – 10-19 Units	$216.42	0.69	$149.33

Figure 4: CRB Replacement Values (Climate Ready Boston, 2016)

Displacement costs and business interruption costs will be calculated using similar sources and approaches as the determination of property damage costs. When calculating climate change damage costs, impacts from SLR, extreme heat, storm surges, and riverine flooding events are usually included. The team will only focus on SLR as this will cause a large portion of damage and necessary relocation to the City of Boston.

The costs from these newly affected areas will be added to the damage, relocation, and business costs from SLR that CRB determined. The total damage costs will then be compared to the cost of all of the projects the City of Boston is planning to do to prepare for the effects of SLR. This will give a very rough estimate of how much money (in present dollars) Boston will save or lose by implementing these projects.

3.3 Sensitivity Analysis of Social Vulnerabilities

The team will use information gathered from the census on vulnerable populations to identify the most vulnerable areas of the City. The Environmental Justice (EJ) Neighborhoods layer on GIS displays data for minority populations, income, and english isolation, and all possible combinations of the three. (*Environmental Justice Viewer*, n.d.). The EJ layers will be overlaid in GIS on a map of the City to show which areas have the highest concentration of vulnerable populations. In addition to the EJ GIS data, the team will evaluate the spatial data of socially vulnerable groups used in CRB for other vulnerabilities such as age, persons with medical disabilities, and persons with illnesses. This, along with the 44" SLR layer, will reveal which areas of the City should be prioritized when developing new projects.

3.4 Design Component

It is unclear how long it will take the team to complete the first objectives and how extensive the analysis will be. Therefore, a decision tree (shown in Figure 5) was made to detail the team's decision-making process as the work continues in B term. The steps labeled 'Option 1' represent the team's preference of final deliverables for the project. 'Option 2' and 'Option 3' are potential necessary adaptations as the team begins to tackle objectives. These options are further discussed below.

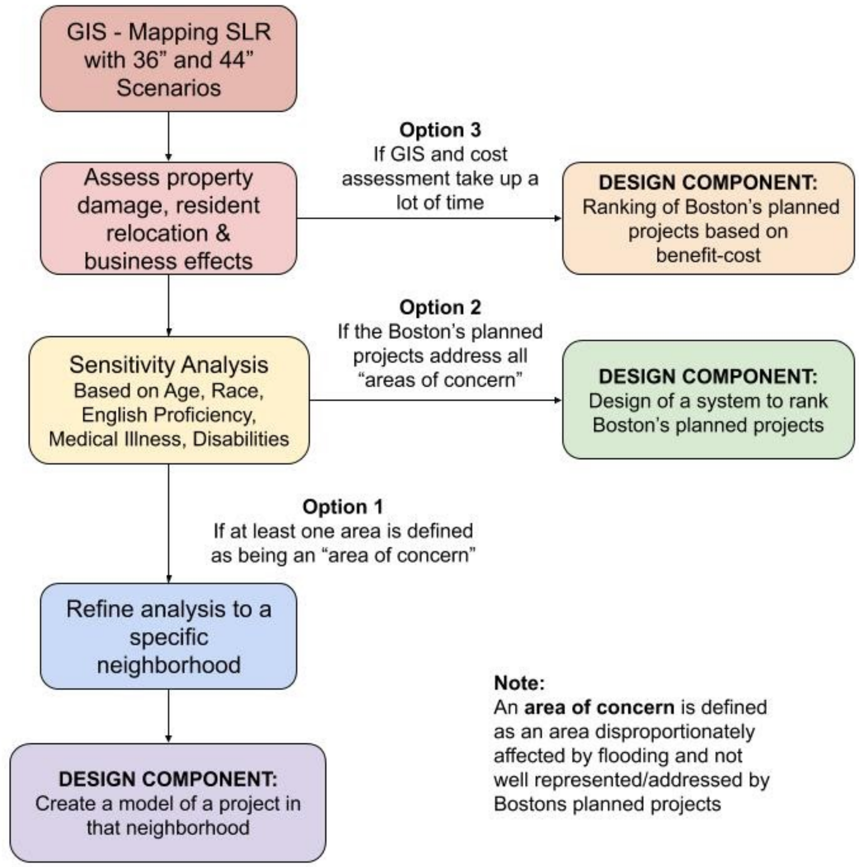


Figure 5: Methodology Decision Tree

3.4.1 Option 1: Create Neighborhood Project Model

The team will take a deeper look at the three neighborhoods, East Boston, Charlestown, and South Boston as there have already been project proposals made for these areas. For these neighborhoods a sensitivity analysis of residents will be conducted. Sensitivity is the degree to which groups of residents are disproportionately affected by emergency situations and climate change effects. Investing more time and resources into the preparedness level of these groups is necessary to ensure they are afforded the same protections as other groups in the City. Each of the three neighborhoods will individually be evaluated for most vulnerable populations. Each vulnerable demographic group's population will be multiplied by a sensitivity factor to provide an index of vulnerability. Several simulations will be run for each neighborhood, each time a different vulnerable group will be prioritized in the simulation. Prioritizing a certain group means that they are identified as the most vulnerable population and therefore will be assigned a high sensitivity factor to reflect this vulnerability. The scenario will be repeated with each type of demographic to help the team to better understand where the most vulnerable populations live throughout the City and what areas will be most at risk in a given scenario. The scores will be used to identify the neighborhood with the highest population of vulnerable groups and the area of focus for further assessment.

After identifying the neighborhood with the highest population of vulnerable groups the team will take a deeper look at the distribution of projects throughout that community. The team will assess if projects in the neighborhood are designed to protect the most vulnerable residents of the community. If they do not, the team will design a project model to address SLR impacts on vulnerable groups derived from the social vulnerability analysis. Given time constraints, the team recognizes this work may not be feasible. As an alternative to a new conceptual design, the team may instead refine a planned City project to prevent SLR damage.

3.4.2 Option 2: Boston Planned Project Ranking based on Cost & Social Vulnerability Analysis

If the team has enough time for GIS modeling, cost analysis, and sensitivity analysis but not enough time to fully design a project model, the team will focus on Option 2. In this option, the team will rank projects based on their cost to benefit ratio and their impact on vulnerable populations. The deliverable is a prioritized list of projects that will help determine the next best steps in SLR preparedness for the City.

3.4.3 Option 3: Boston Planned Project Ranking based on Cost Analysis

If the GIS modeling and cost analysis due to SLR take extensive time for the team, the final deliverable of the team will be to design a framework to rank Boston's planned SLR protection projects. This can be seen in Figure 5 as the Option 3 Design Component. This ranking will be a prioritization of planned projects that will benefit the most at risk sections of the city based on the cost analysis of SLR, not taking into account sensitivities of various social/demographic groups.

3.6 Proposed Timeline

Below in Figure 6 is the proposed project timeline for B term 2020. Time has been dedicated to completing each objective and writing the final report. A more detailed version of this chart can be found in Appendix A.

	B Term							
Task	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
CRB Method Replication								
Cost Analysis								
Sensitivity Analysis								
Design Component								
First Draft Final Report								
Second Draft Final Report								
Final Report								
Final Presentation								

Figure 6: Project Timeline for B Term

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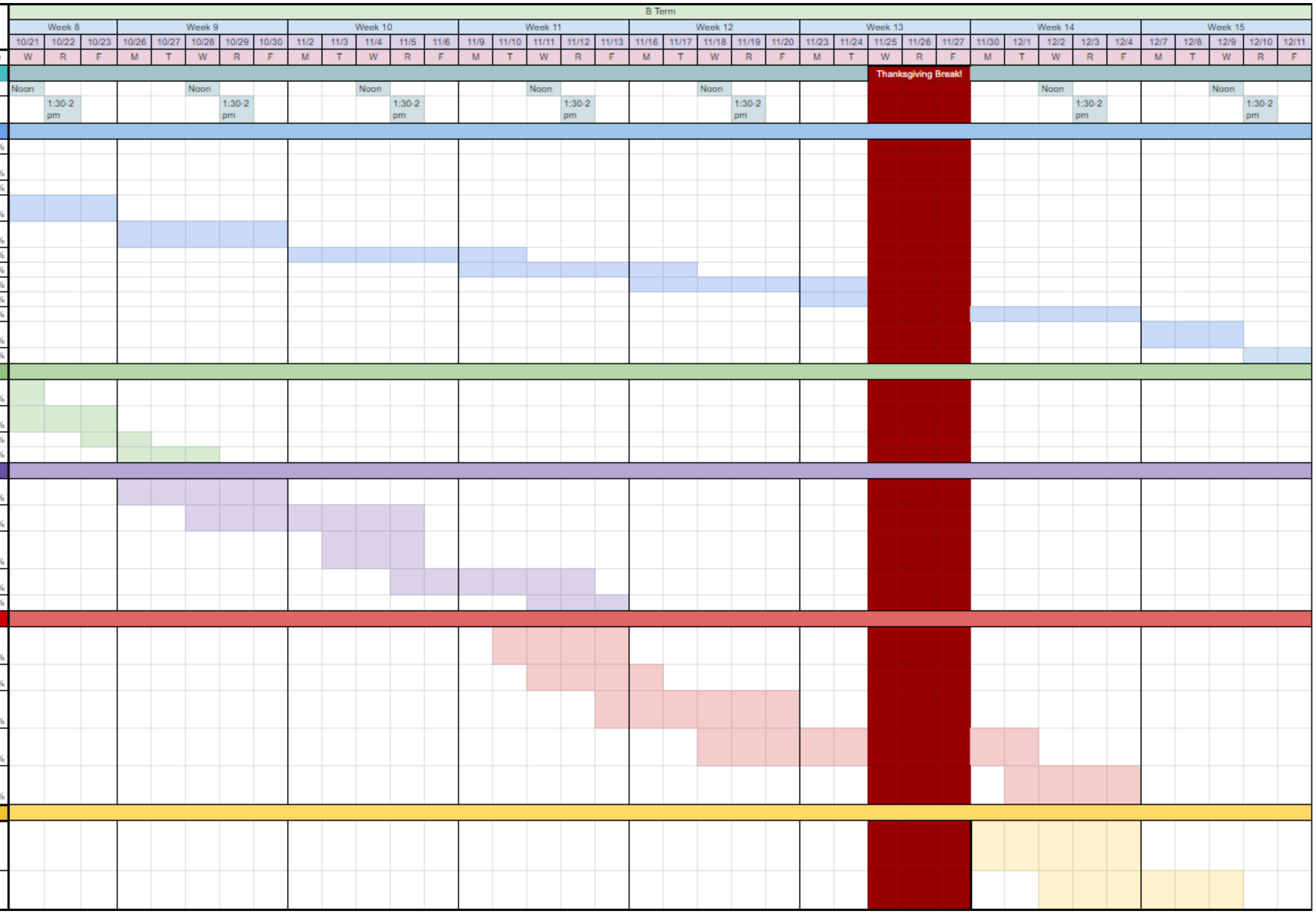
Appendix A: Detailed Project Gantt Chart

Below is the detailed project timeline, the full chart can be found here.

Project Timeline

#	Task	Lead	Due Date	Percent Done
	Meetings			
1	Advisor Meeting	Rotating	N/A	N/A
2	Meeting w/ Dave and Stef	Rotating	N/A	N/A
	Writing Tasks			
1	Rough Draft Project Proposal	All	10/2	100%
2	Submit Second Draft to Advisors	All	10/8	50%
3	Send Final Draft to Stantec	All	10/14	0%
4	Address proposal feedback from Stantec	All	10/23	0%
5	Update Tense throughout the doc to past	All	10/30	0%
6	Write Results	All	11/10	0%
7	Write Conclustions	All	11/17	0%
8	Write Recommendations	All	11/24	0%
9	First Project Draft to Advisors	All	11/24	0%
10	Second Draft to advisors	All	12/4	0%
11	Submit Final Report to Advisors and Stentec	All	12/9	0%
12	Final Presentation	All	12/10 or 12/11	0%
	CRB Method Replication			
1	Create Shared Folder for map and other files	Hannah	10/21	100%
2	Find and Download demographic/flood layers	All	10/23	25%
3	Add all layers to map	All	10/26	0%
4	Asjust 36" SLR layer to be 44"	Lauren	10/28	0%
	Calculating Costs			
1	Explore and get familiar with HAZUS	Hannah	10/30	0%
2	Do HAZUS assement of focus neighborhoods	Trisha	11/15	0%
3	Down load raw data about demographics, property damge etc into excel files	Chase	11/5	0%
4	Calculate additional damages due to extra SLR	All	11/12	0%
5	Find CB ratio of each project	Emilia	11/13	0%
	Sensitvity Analysis			
1	Identify neighborhoods with highest concentration of vulnerable populations	Trisha	11/13	0%
2	Plot proposed project locations on map	Lauren	11/13	0%
3	Conduct sensativity analysis of three neighborhoods with projects	Chase	11/18	0%
4	Identify neighborhood that has the highest population of vulnerable groups	Emilia	12/1	0%
5	Determine if projects proposed in this neighborhood protect the most vulnerbale	All	12/4	0%
	Design Compenent: Neighborhood Project Model			
1	Identify project in the neighborhood that will not protect residents against new SLR projections	All	12/4	
2	Create design model of how to adapt this project to protect residents in the future	All	12/10	



Appendix B: Cost Analysis Preprocessing Data

Hazus	Occupancy Code	BRV	CSRV	CRV
RES1	Single Family Dwelling	$143.14	0.69	$98.77
RES2	Mobile Home	$137.47	1.14	$156.71
RES3A	Multi Family Dwelling - Duplex	$117.76	0.69	$81.25
RES3B	Multi Family Dwelling – 3-4 Units	$227.31	0.69	$156.85
RES3C	Multi Family Dwelling – 5-9 Units	$227.31	0.69	$156.85
RES3D	Multi Family Dwelling – 10-19 Units	$216.42	0.69	$149.33
RES3E	Multi Family Dwelling – 20-49 Units	$209.84	0.69	$144.79
RES3F	Multi Family Dwelling – 50+ Units	$202.67	0.69	$139.84
RES4	Temporary Lodging	$211.01	0.69	$145.59
RES5	Institutional Dormitory	$242.70	0.69	$167.46
RES6	Nursing Home	$246.88	0.69	$170.35
COM1	Retail Trade	$137.67	1.19	$163.82
COM2	Wholesale Trade	$133.41	2.07	$276.16
COM3	Personal and Repair Services	$160.45	2.36	$378.66
COM4	Business/Professional/Technical Services	$198.63	0.54	$107.26
COM5	Depository Institutions	$299.43	0.54	$161.69
COM6	Hospital	$426.82	0.54	$230.48
COM7	Medical Office/Clinic	$241.96	0.54	$130.66
COM8	Entertainment & Recreation	$252.25	1.7	$428.83
COM9	Theaters	$211.95	0.54	$114.45
COM10	Parking	$89.34	0.54	$48.24
IND1	Heavy	$151.75	2.07	$314.12
IND2	Light	$133.41	2.07	$276.16
IND3	Food/Drugs/Chemicals	$205.59	2.07	$425.56
IND4	Metals/Minerals Processing	$205.59	2.07	$425.56
IND5	High Technology	$205.59	2.07	$425.56
IND6	Construction	$133.41	2.07	$276.16

Hazus	Occupancy Code	BRV	CSRV	CRV
AGR1	Agriculture	$133.41		$0.00
REL1	Church/Membership Organizations	$213.29	0.55	$117.31
GOV1	General Services	$169.99	0.55	$93.49
GOV2	Emergency Response	$283.68	1.5	$425.52
EDU1	Schools/Libraries	$228.41	1	$228.41
EDU2	Colleges/Universities	$200.58	1	$200.58

Appendix C: PTYPES to Hazus Code

P_TYPES	HAZUS Code
13	COM1
31	COM1
101	RES1
102	RES3B
103	RES2
104	RES3A
105	RES3B
106	case by case
108	COM10
109	case by case
110	RES3B
111	RES3C
112	RES3E
113	RES3F
114	RES3F
116	COM10
117	RES6
118	RES6
119	COM10
120	RES3F
121	RES4
122	RES4
123	RES5
124	RES5
125	RES3
126	RES3
127	RES3
128	RES3B
129	RES5
130	case by case
131	case by case
132	case by case
300	RES4
301	RES4
302	RES4
303	COM8
304	RES6
305	COM6
306	case by case
307	IND3
309	COM7
310	COM3
311	COM3
312	COM2
314	COM3
315	COM2
316	COM2
317	COM2
318	COM2
319	COM1
320	COM1
321	COM1
322	COM1
324	COM1
325	COM1
326	COM8
327	COM8
328	COM8
329	COM8
330	COM1
331	COM3
332	COM3
333	COM3
334	COM1
335	COM3
336	COM10
337	COM10
338	COM10
339	COM10
340	COM4
341	COM4
342	COM7
343	COM4
344	COM4
345	COM4
346	COM4
347	COM4
348	COM4
350	GOV1
351	EDU1
352	EDU1
353	COM8
355	COM8
356	RES3
357	RES3
358	COM4
359	COM10
360	COM8
361	COM8
362	COM9
364	COM9
365	COM9
369	COM1
370	COM8
374	COM8
375	COM8
376	COM8
377	COM8
378	EDU1
379	REL1
384	COM8
387	COM10
388	COM10
389	RES 1
390	case by case
395	COM3
400	IND1
401	COM2
402	COM2
404	IND2
406	IND5
407	IND1
414	IND3
420	IND3
437	IND5
438	IND5
439	COM4
446	COM4
465	case by case
901	GOV1
902	GOV1
903	GOV1
904	EDU2
905	case by case
906	REL1
907	RES3C
908	GOV1
941	COM8
945	case by case
954	COM7
958	COM7
962	COM10
970	REL1
973	COM4
974	GOV2
976	EDU1
978	COM8
979	COM6
980	COM4
985	case by case
986	case by case
991	COM4
995	RES3B

Appendix D: Community Survey

Sea Level Rise Perceptions [open ended/value input questions]

1. Have you heard of Climate Ready Boston before?
2. What is your level of concern for future impacts of flooding in your neighborhood?
3. What comes to mind when you hear “sea level rise”?
4. How likely do you believe a major flooding event will occur…(likelihood %)?
    a. In the next 5 years
    b. In the next 10 years
    c. In the next 50 years
5. Have you ever lived through a flooding event within your neighborhood?
6. Do you feel as though your neighborhood is prepared for future floods in your area?
7. How often do you speak with others in your neighborhood about flooding?
8. How many inches do you believe SLR will increase by 2070?

Climate Change Perceptions

1. How dangerous do you view the threat of climate change to your neighborhood?
2. How do you feel about Boston's city-wide planning for climate change effects?
3. How important do you feel it is to protect against sea level rise?
4. How do you view your role in decreasing emissions to prevent climate change?

Neighborhood Values

1. What is your favorite part of your neighborhood (this can be a program, a physical location etc.)?
2. What part of the neighborhood do you wish could be improved? How?
3. On a weekend, how likely are you to stay within your neighborhood?
4. How would you like to see your local green space improved?
5. How often do you often visit the waterfront along Condor Street?
6. Have you heard of seawalls used to protect against flooding? Do you believe these projects are an effective method of protection?
7. Have you heard of an elevated harbor walk to protect against flooding? Do you believe these projects are an effective method of protection?

Appendix E: Links to Additional Maps

Maps were created for each of the CDC's vulnerability categories:

- Housing Type and Transportation Map
- Minority Status and Language Map
- Socioeconomic Map
- Household Composition & Disability Map

East Boston Flood Depth Maps

Maps were created for the 36 in SLR and the SLR to the 14 ft contours to show flood depth:

- East Boston 14' Contours Flood Depth Map
- East Boston 36" SLR Flood Depth Map

East Boston SVI and Flood Depth Maps

Below are links to the maps the team created that overlay the SVI categories with East Boston's flood depths up to the 14 ft contours:

- Socioeconomic Map
- Household Composition and Disability Map
- Minority Status and Language Map
- Housing Type and Transportation Map

Maps were also created for comparison to the 36" SLR flood depth:

- Socioeconomic Map
- Household Composition and Disability Map
- Minority Status and Language Map
- Housing Type and Transportation Map
- Summary Map

Appendix F: Alternative Analysis Location 1

Table 12. Alternative Analysis Results at Location 1

Design Options	Environmental Impact	Cost	Community Perception	Longevity/ Sustainability	Design Feasibility	Operation and Maintenance
Replace Existing Wall	High[1]	$650,000[2]	Fair[3]	Extensive[4]	Moderate[5]	$2,000-$6,000[6]
Elevated Harborwalk Along Wall	High[7]	$4,600,000[8]	Good[9]	Extensive[10]	Difficult[11]	$16,000-$28,000[12]
Do nothing	None	None	Poor[13]	Limited[14]	None	None

1. Involves removal of trees and coastal grasses, and significant construction/armoring of coastline.
2. $88,000 for the retaining wall with 30% contingency totals $114,000 per 100 linear feet, with 550 linear feet, total comes out to $629,200 or $650,000 rounded (Boston Public Works Department, 2018, p. 60-61). Note: Assumptions of Retaining Walls costs by BPWD: Includes costs of installation, excavation, rebar, concrete, crushed stone backfill, filter fabric, and waterproofing. No ground improvement was assumed.
3. Offers protection from SLR but does not create any new community space or neighborhood beautification.
4. 50-100 years
5. Replacement will require extensive structural considerations.
6. Based on seawall annual maintenance $2000-$6000, waterproofing repairs, chinking stones, repairing cracks (Boston Public Works Department, 2018, p. 42).
7. Involves removal of trees and coastal grasses, and significant construction/ armoring of coastline.
8. The barrier would costs $843,700 per 100 linear feet (seawall 4’ extension would cost $23,000, $176,000 for 6’ retaining walls, $20,000 for handrail, $101,000 for roadway and sidewalks, $44,000 for the storm water system, $232,000 for water and sewer utilities, $32,000 for street lighting, $16,000 for a crest path, $5,000 for erosion control plantings, and 30% contingency at $194,700) totaling $4,640,360 for a 550 linear foot harborwalk (Boston Public Works Department, 2018, p. 42-43, 60-61).
9. Creates community space that improves scenic views.
10. 50-100 years
11. Location has significant space constraints and building seaward is inevitable.
12. Annual inspections & storm inspections $6000-$8000, seawall maintenance $2000-$6000, handrail maintenance $1000-$3000, outfall maintenance $1000-$2000, vegetation maintenance $6000-$9000. Note: Roadway & Sidewalks, Storm Water System, Water and Sewer Utilities and Street Lighting costs were added to the Harborwalk Flood Barrier cost

estimates based on pg. 60-61 Sample Raised Roadway. These elements would need to be considered to elevate the current design with the Harborwalk Flood Barrier.

13. Residents will likely be unsatisfied as no protective measures are being taken.
14. Significant flooding may not occur for 35-50 but there will be no protection for when it does.

Appendix G: Alternative Analysis Location 2

Table 13. Alternative Analysis Results at Location 2

Design Options	Environmental Impact	Cost	Community Perception	Longevity/ Sustainability	Design Feasibility	Operation and Maintenance
Deployable Floodwall at entrance to Urban Wild, 12ft wide[15]	Low[16]	$6,900[17]	Good[18]	Extensive	Good[19]	No exact costs associated with operation and maintenance[20]
500 ft^2 elevated pier at corner of wall and Urban Wild [21]	Medium[22]	$102,000-$196,000[23]	Good[24]	Moderate	Limited[25]	$1,500-$3,000[26]
Elevated Vegetated Berm	Low[27]	Less than $100,000[28]	Fair[29]	Extensive	Good[30]	$14,000-$20,000[31]
Do nothing	None	None	Poor	Limited	None	None

15. The 12-foot width was obtained using the measuring tool in Google Earth
16. Low, additional fill would be required on adjacent berm.
17. Cost is dependent on width and desired height of the floodwall. Climate Resiliency Design Standards and Guidelines. $315/lf - 4 ft. Height, $415/lf - 5 ft. Height , $575/lf - 6 ft. Height, $660/lf - 7 ft. Height, $750/lf - 8 ft. Height. (Additional $10/lf for anchors). Width is 12ft. Height of the desired floodwall is 6ft. Cost calculation: $575/lf x 12 ft = $6,900. *Width is not exact. (Climate Ready Boston, 2018).
18. Favorable; has been completed in other areas of Boston and has worked well. Protects the community living in the area, along with businesses.
19. Used successfully for other projects in the City.
20. For assembly and retraction, cost is dependent on crew size, wage rate, and transportation needs. The deployable floodwall is the only active design option, meaning it requires attention.
21. The 500 sq. feet was obtained using the measuring tool in Google Earth.
22. Would remove access to the beach which would lead to less trash on the beach.
23. Construction will cost $125 to $300 per square foot (August, 2020) for a total of $62,500 to $150,000. Floodproofing will cost $40,277.78 to $45.833.33 (Climate Ready Boston, 2018, p. 26). This number was found by taking the total cost of flood proofing Fish Pier (29 to 33 million) and dividing it by the square footage of the pier (360,000) and then multiplying that number by the square footage of the near pier.

24. Most likely favorable; residents would be able to use the area as a lookout over the harbor and signage could be placed to educate about climate change and how the pier protects residents
25. CRB has created designs to waterproof large piers but no projects exist at this small of a scale for climate resiliency.
26. Maintenance costs are expected to be 1.5 percent of the implementation cost (Climate Ready Boston, 2018, p. 28).
27. Lower impact: significant fill added, still allows for previous surface for stormwater runoff. Impacts young tree plantings.
28. Assuming less than 100 linear feet needed, (Climate Ready Boston. 2018, P. 27)
29. Potential conflict of coastal views from sidewalk, however elevated berm blocking full coast is adjacent. Loss of park entrance ADA accessibility.
30. Used successfully for other projects in the City.
31. Annual Inspection and Storm Inspection \$6,000-\$8,000, Vegetation maintenance \$8,000-\$12,000.

Appendix H: Alternative Analysis Location 3

Table 14. Alternative Analysis Results at Location 3

Design Options	Environmental Impact	Cost	Community Perception	Longevity/ Sustainability	Design Feasibility	Operation and Maintenance
Elevate vegetated berm in front of entrance	Low	Less than $100,000[32]	Fair	Extensive	Good	$14,000-$20,000[33]
Deployable floodwall at entrance, 10ft wide[34]	Low	$5,750	Good	Extensive	Good	No exact costs associated with operation and maintenance[35]
Storm grate connected to a drainage pump and tank	Moderate[36]	$365,000[37]	Poor[38]	Extensive[39]	Difficult[40]	$3,000+ per year[41]
Do Nothing	None	None	Poor	Limited	None	None

32. Assuming less than 100 linear feet.
33. Annual Inspection and Storm Inspection $6,000-$8,000, Vegetation maintenance $8,000-$12,000.
34. The 10-foot width was obtained using the measuring tool in Google Earth
35. For assembly and retraction, cost is dependent on crew size, wage rate, and transportation needs. The deployable floodwall is the only active design option, meaning it requires attention.
36. Some environmental impact after initial construction as small animals could be entrapped (Commonwealth of Massachusetts, n.d., p. 2).
37. $44,110.57 for the storm grate and piping: $2142.86 for mobilization, $8.75 for linear foot for surface material removal, $2,725 for grate, $71.50 to $176 per linear foot for storm drain pipe, $2,550 to $3,340 for manhole, $4.50 per ton of trench backfill, $10.50 per ton for bedding materials, $19.50 per square yard for roadway patching, $150 per day for traffic control, $15,000 for landscaping and surface restoration , and an additional 20% for engineering and construction contingencies (City of Riverdale, 2009, p. 2-3). The total cost for the storm grate was found by taking the average cost per catch basin of the Riverdale projects for each of the components mentioned previously and adding up the numbers. 321,684 for the pump station and tank: $1,500 per horsepower for installation, $10 per barrel for the tank, and an additional 20% for engineering and construction contingencies (Menon, 2015, Chapter 13). It was assumed that the pump would operate with 20 horsepower as it would be a relatively small

pump (Broward County Water and Wastewater Division, 2011, p. 3). It was also assumed that the tank would be able to hold 23,807 barrels (3785 cubic feet) of stormwater since that is the daily transmission rate of smaller pump stations (Cost Water, 2020).

38. Less invasive than other projects, the community would probably not even notice it.
39. (Commonwealth of Massachusetts, n.d., p. 2)
40. Similar drains are used for bridges, tunnels, and parking lots. However, since Boston drains to the ocean and the sea level will be above the storm grate in this scenario the design may not be feasible.
41. $36.36+ for regular cleaning to remove debris from storm grate and pipes (BWSC, 2020, p. 5) and $2,812+ for inspections and repairs (Narayanan & Pitt, 2006).