MQP-PPM-1892

ASSESSING AND REDUCING THE IMPACTS OF FLOODING ON TRANSPORTATION IN THE CITY OF CHELSEA, MASSACHUSETTS

A Major Qualifying Project
Submitted to the Faculty of the
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirement for the
Degree in Bachelor Science in
Civil Engineering
By

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Abstract

This project assessed the transportation resiliency to accommodate increased storm events and predicted sea level rise for the City of Chelsea, MA, with a focus in the city's Marginal Street area. Several flood mitigation strategies were evaluated, taking into account limitations of Chelsea's geography. We determined that Chelsea should implement a sea wall structure to accommodate future sea level rise and flooding, and provided recommendations for responses to flooding by analyzing flooding, traffic impacts, resiliency, and design feasibility.

Acknowledgements

We would like to extend thanks to the following people for their contributions to our project:

Mr. Alex Train, Planning and Development, City of Chelsea, MA

Mr. John DePreist, AICP, Director of Planning & Development, City of Chelsea, MA

Professor Paul Mathisen, Project Advisor, Associate Professor, WPI

Professor Mingjiang Tao, Project Advisor, Associate Professor, WPI

Professor Suzanne LePage, Instructor, WPI

Authorship

This written report, as well as the design development process, was a collaborative effort. All team members, Megan Concannon, Austin Fabbo, Francesca Ferrero, Luke Fronhofer, and Sarah Sanchez contributed equal efforts to this project.

Megan Concannon

Megan worked on the GIS visualization of flooding, including generating the map images in GIS and analyzing the impacts of the flooding. She also worked on the traffic detour suggestions for the City of Chelsea in each flooding scenario as an extension of this work.

Austin Fabbo

Austin was one of our main writers and focused on the resilience of the transportation network. He worked with Luke to access and grade Chelsea with the 4R/5C model. Austin also helped with editing the report.

Francesca Ferrero

Francesca worked on the GIS visualization of flooding, including generating the map images in GIS and analyzing the impacts of the flooding. She also worked on the traffic detour suggestions for the City of Chelsea in each flooding scenario as an extension of this work.

Luke Fronhofer

Luke worked with Austin on characterizing the resilience of the transportation network of Chelsea and served as a secondary point of reference for the design section. He also completed the final formatting for the report.

Sarah Sanchez

Sarah worked on the design selection an evaluation of this report. She compared multiple potential design solutions, and fully calculated the design requirements for two concrete block sea walls, one each for 2030 and 2050 flooding, leading to a cost analysis and AutoCad model.

Capstone Design Statement

The goal of this Major Qualifying Project was to develop a design plan to mitigate the effects of climate change in the City of Chelsea, MA, focusing on flooding due to sea level rise and storm events in the Marginal Street traffic corridor. The capstone design requirement was satisfied through the design of a sea wall to combat rising sea levels and a traffic detour plan to minimize disruption to major transportation routes as a result of flooding.

This capstone design process represents an opportunity for those involved to elevate their educational experience at Worcester Polytechnic Institute as they prepare to become professional engineers. Each student in this Major Qualifying Project synthesized learned knowledge from their course history to demonstrate that all students achieved design competence in their selected curriculum areas within the realm of Civil Engineering. These students and their selected curriculum areas are:

- Megan Concannon - Environmental Engineering
- Austin Fabbo - Project Management
- Francesca Ferrero - Urban Planning
- Luke Fronhofer - Transportation Engineering
- Sarah Sanchez - Project Management

As a capstone design experience, this project included the analysis of traffic and flood data to evaluate the impact of flooding on the Marginal Street area. This analysis was used to propose an alternate traffic plan in the event of several flooding scenarios to be implemented at the discretion of the City of Chelsea. It also involved a theoretical analysis of the city's network resilience. Additionally, it involved the structural calculations for the design of a seawall in accordance with the Port Authority and other relevant regulations. This project also involved interdisciplinary coordination, engineering principles, and economic and environmental implications.

Interdisciplinary Coordination

Any major project requires consistent and productive coordination across disciplines and between all members of the team. In this case, the final products of the project incorporated two separate solutions to future flooding, to be incorporated into one final report and presentation. In order for all deliverables to be cohesive, all involved will need to maintain open lines of communications at all points throughout the project. This was accomplished through weekly team meetings, weekly advisor meetings, shared online documents, and consistent emails and instant messaging.

Engineering Principles

In order to complete the Major Qualifying Project, the team used the following tools and methods as a part of the capstone design experience:

- Allowable Stress Design to determine the minimum design requirements for a proposed sea wall along Marginal Street
- RISA 3D to verify hand calculations for proposed seawall design
- Traffic Analysis to determine the optimal traffic solution to flooding with the least disruption to average daily traffic
- AutoCAD 3D to model the proposed sea wall design
- ArcGIS to model future flooding scenarios and display risk to various structures

Economic and Environmental Implications

For this Major Qualifying Project, the team acknowledges the ethical standards to which engineering and design work must be completed. There are certain economic and environmental implications involved with the proposed solutions in our project which require the team to operate with the utmost honesty and integrity. The proposed solutions aim to minimize environmental and economic impacts by maximizing the sustainability of all designs or plans. In part this was achieved through compliance with existing ordinances.

Professional Licensure Statement

Professional licensures are a type of certification that seeks to enforce standards within an industry. In the United States, engineers are licensed by states and required to be licensed by the state in which they practice. To maintain a status of prestige and high level of regard for human safety, the requirements for becoming licensed are difficult and time consuming with specific requirements varying state to state.

To become a Professional Engineer there are several requirements that are uniform across all states: You must graduate from an ABET-accredited college, pass the Fundamentals of Engineering (FE) Exam, accumulate four years of progressive engineering experience, then pass the Principles and Practice of Engineering exam. Once you pass the final exam you become a Professional Engineer; however, to maintain the status of Professional Engineer you must continue education and keep up to date with the latest industry standards (ASCE, 2014).

Only after one passes the PE exam are individuals authorized to practice engineering in a professional capacity. This means that individuals take legal responsibility for their work and can provide engineering services to the public without oversight of other Professional Engineers. Becoming a Professional Engineer shows that an individual has a strong understanding of the fundamentals of engineering, industry experience, and has a working knowledge of their ethical responsibilities. By regulating who can hold the title of Professional Engineer, a professional licensure can maintain a high standard to protect the public, individuals, and the profession. The purpose of authorizing only those individuals who have met the standards of Professional Engineers is to achieve a higher quality of work within profession. The majority of Civil Engineering projects impact the public; therefore, a higher quality of work aims to protect the public from potential engineering disasters. In addition, licenses serve as a safety precaution; designs are required to be reviewed and stamped by a Professional Engineer before being implement.

Executive Summary

Flooding due to the impending effects of climate change is an impending reality for coastal cities around the world. As the climate trends to a warmer trajectory, the frequency of annual storms will increase. The City of Chelsea Massachusetts is one of these coastal areas in question. The goal of this project was to analyze the potential impacts of major storm events on the city of Chelsea while assessing the city's current levels of resiliency.

Introduction and Background

The City of Chelsea faces increasing risk of flooding from sea level rise and severe weather patterns. This project explored the extent to which flooding would impact the city to evaluate and improve resiliency. Our team modeled fifty and one hundred year storms and sea level rise predictions in 2030 and 2050. Modeling these allowed us to identify the streets and businesses that would be rendered inaccessible in each scenario. The models, or maps in GIS software, are important to identify areas of improvement for how the city prepares for, responds to and recovers from flooding events.

Methods

The measures the city puts in place to mitigate the impacts of flooding events is how we measured their resiliency. This includes measures the city has in place currently to prepare for flooding events, such as roadways and bridges built to withstand flooding, evacuation routes, and plans for shelters or aid. Resiliency also looks at the recovery from flooding events, including time to repair damages and return to normal operations. Our team reviewed the current measures outlined in the city's Hazard Mitigation Plan and looked at previous flooding events to gauge the current resiliency and identify areas of improvement, including traffic detour routes and design solutions.

There are a variety of design measures coastal cities can use to increase resilience to flooding; these solutions range from small measures like strategic landscaping and improved drainage systems to more severe measure like sea walls. Our team reviewed a selection of design measures that could possibly serve as the best solution for the City of Chelsea. We considered the needs the solution must serve, such as the predicted water level, as well as the restrictions or design limitations, such as the Port Authority limitations and the topography. This led to a recommendation and engineering analysis of a solution for the Marginal Street Area.

Results

The results of the data collected showed that Chelsea faces significant problems in the coming years from climate change and the resulting sea level rise. The GIS visualizations created by the team show the extent of sea level rise on Chelsea in 2030 and 2050. We have determined that 4 % of the current city will be underwater in 2030 and 13% of the current city will be underwater in 2050. Based on these projections we have created three transit scenarios: a vehicle commuter through Chelsea, the MBTA Silver Line 3, and the MBTA Commuter Rail in the event of road closures.

The group's network resiliency analysis determined that while the city government is well prepared for potential disasters, the population of Chelsea is less prepared. Our results mirror the Centers for Disease Control and Prevention's (CDC) social vulnerability index assessment of the City of Chelsea.

Conclusion and Recommendations

This MQP provided the City of Chelsea with a greater understanding of potential impacts of flooding along with several possible ways for mitigating the impacts. Our work resulted in the creation of several flood maps and resilience analyses. We used these to create recommendations for the City of Chelsea to improve their resilience from flooding risks. As part of this, we designed a sea wall to reduce the impact of flooding along Marginal Street.

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1. Introduction

The Earth is currently in a warming period, which affects the vulnerability of coastal cities to sea level rise and flooding. Since the 1800's the average temperature of the Earth has increased by 1.92 degrees Fahrenheit, as humans continually release greenhouse gases into the atmosphere. Using ice cores drawn from glaciers around the globe, the National Research Council (NRC) proved that the Earth's climate varies in response to these greenhouse gases (2017). As carbon dioxide emissions continue to increase, the planet has seen the five hottest years on record in the past decade alone (NRC, 2017). The effects of a warming Earth on various climates around the planet stem from this upward trend in global temperature.

More specifically, the International Panel on Climate Change (IPPC) highlights the acceleration of sea level rise beginning in the 1900's as a result of climate change (2018). Decades later, analysis of research and samples by the International Drilling Program and the U.S. National Science Foundation estimates that a sustained period of two degrees Fahrenheit temperature rise could lead to between 20 and 30 feet of sea level rise (Wilson, et al., 2018). According to the Penn State Earth System Science Center, as many as 650 million people around the globe live on land that is at risk of being chronically or permanently flooded due to sea level rise (Maines, 2018). The East Coast of North America, in the Atlantic and Gulf Area, is expected to see a steep increase in coastal and tidal flooding due to low flooding thresholds and a sinking coastline. Many East Coast communities are now seeing dozens of tidal floods each year. Some communities have seen a fourfold increase in the annual number of days with tidal flooding since 1970. In the next 15 years, two-thirds of these communities could see a tripling or more in the number of high-tide floods each year. (Spanger-Siegfried, 2014).

The City of Chelsea, Massachusetts, which covers approximately two squares miles northeast of Boston, is one these vulnerable East Coast communities as sea levels rise and floods increase in frequency. The map in Figure 1 shows the Marginal Street area in Chelsea, which is focus of this project and a key transportation route in the city that is susceptible to flooding events. Through truck traffic along this route and surrounding routes is three to five times higher than similar regional areas, and total traffic is expected to increase over 13% with the addition of a casino to the Boston area (Stantec, 2018). The City Planning Department is aware of the looming threats to Chelsea's infrastructure, and is actively seeking solutions to increase the flood resiliency of the local transportation network along the Marginal Street corridor.

Figure 1. Map highlighting the area of Marginal Street in Chelsea where the project is focused.

This Major Qualifying Project was done in collaboration with the City of Chelsea as our sponsors to develop recommendations and actionable plans to prepare the Marginal Street area for increased flooding and storm events. The overall goal was to evaluate the city's transportation network resiliency, which we accomplished through the use of weighted analytical matrices for several aspects of flooding resiliency. We analyzed the effects of increased flooding on the transportation network, including the effects of diverting traffic from flood areas and the effects of flooding on all aspects of transportation infrastructure. We accomplished this by defining parameters for flooding, using predictions for 50 and 100 year storms, and predicted increments of sea level rise over the next 100 years. We used the results of these analyses to highlight the importance of both preventing and mitigating damage from flooding, both to traffic networks and flooding infrastructure. This project included designing a sea wall and traffic detour plan to accommodate flooding events. A set of several recommendations based on our findings have been provided to the City of Chelsea to aid in their efforts to improve their resilience to climate change.

2. Background

Climate change refers to a range of global trends primarily resulting from the release of greenhouse gases in the Earth's atmosphere (IPCC, 2018). Experts predict that climate change will lead to a variety of negative consequences, among them increased frequency of severe weather patterns and accelerated sea level rise (CCSP, 2008). These events have raised concern in coastal communities, like the City of Chelsea, as they recognize a need to prepare for the impending realities of climate change. This chapter will explore the predicted impact of climate change in Chelsea and other areas, specifically focusing on the vulnerabilities along Marginal Street and looking at design cases which may offer viable solutions to the City of Chelsea.

2.1 Impact of Climate Change

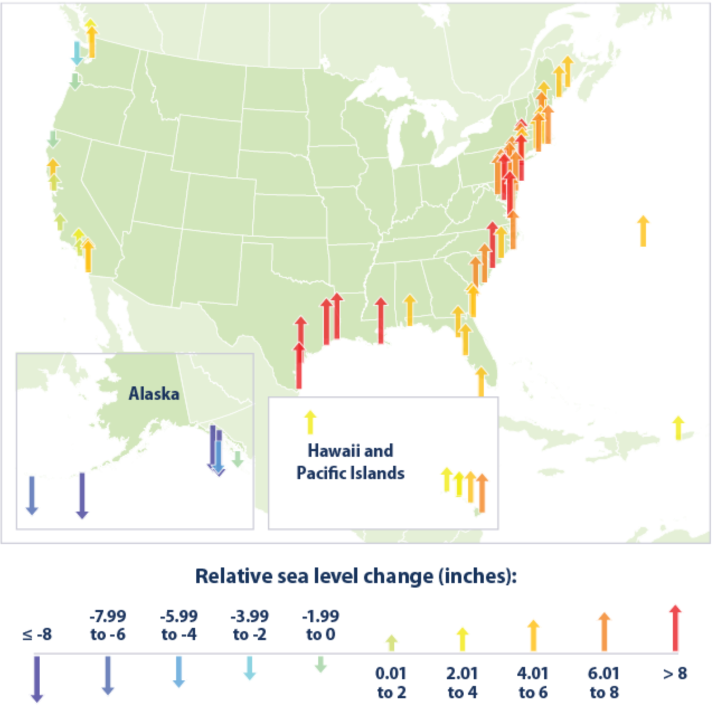
Effects of climate change include rising temperature trends, precipitation patterns, storm surges, sea level rise, and decreasing ice mass. The global temperature increase accelerated global sea level rise resulting in approximately eight inches of rise above 1880 levels, as measured in 2015 (EPA, 2016). This temperature increase will continue to accelerate sea level rise with steady or increasing carbon emissions. As a result a Climate Central analysis found the frequency of damaging flooding would increase throughout the U.S, primarily in coastal cities and communities (Strauss, Tebaldi & Zlemlinksi, 2012).

2.1.1 Potential Impacts of Climate Change in the Northeastern United States.

Climate change will impact coastal areas in a variety of ways. Coastal areas are more vulnerable than inland cities to sea level rise, changes in frequency and severity of storms, warmer ocean temperatures, and increasing precipitation (EPA, 2016). Due to the effects of climate change, coastal cities will face challenges in regards to recovery and resilience of their typical environment, including ecosystems, shoreline erosion, coastal flooding, water pollution, and infrastructure (EPA, 2016). The degradation of these elements will have an impact on coastal city functions and their ability to effectively withstand storms in the future.

Eastern seaboard cities are projected to experience these effects acutely. Figure 2 illustrates that the Eastern seaboard has historically experienced greater increases in sea level compared to other coastal areas in the U.S. For instance, New York City is expected to see two to nine inches of sea level rise with 90% confidence by 2030. Atlantic City will see a four to eleven inch rise, while Bridgeport, CT and Newport, RI will each see a two to nine inch rise. By

2050 sea level rise is expected to more than double in major cities compared to 2030 (Strauss, et al., 2012). In Boston Harbor, the 90% confidence interval for sea level rise is two to nine inches with a "best estimate" of five inches by 2030, and twelve inches by 2050 (Strauss, et al., 2012).



Relative Sea Level Change Along U.S. Coasts, 1960–2014

Figure 2. The map demonstrates relative sea level rise and retreat along U.S. coastlines with a series of color coded arrows (NOAA, 2017).

2.2 Impact of Climate Change on the City of Chelsea

The City of Chelsea is similarly vulnerable to sea level rise and increased flooding. Rates of relative sea level rise from 2000 to 2050 in the Boston area will be between 7.5, 13 and 18 inches "with exceedance probabilities of 83%, 50%, and 17%" respectively, according to the Boston Research Advisory Group. (BRAG, 2016, pp. 6). Extreme models indicate a possible 30 inch sea level rise by 2050, after which sea level rise will continue to accelerate (BRAG, 2016). Estimates for sea level rise in the year 2100 show water levels at a projected maximum of 7.5 feet from 1880 levels. Projected sea level rise will eventually drown saltwater marshes and become tidal flats and sub-tidal bays (BRAG, 2016). These transition habitats serve as a buffer zone between the ocean and land. Saltwater marshes are able to ease the effects of low grade storms but flooding from climate change will greatly hinder these ecosystem's capabilities (New

Hampshire Department of Environmental Services, 2004). In addition, rising sea levels increase wave energy, tidal range, and inundations resulting in further erosion of the coastline (BRAG, 2016). The City of Chelsea, just north of Boston, will experience the effects of sea level rise most severely along Chelsea Creek and the adjacent roadways, Marginal Street and Eastern Ave. Figure 3 shows Marginal Street within the blue circle. The Chelsea Creek which runs parallel to the street is connected to the Boston Harbor and is predicted to rise congruently with sea levels.

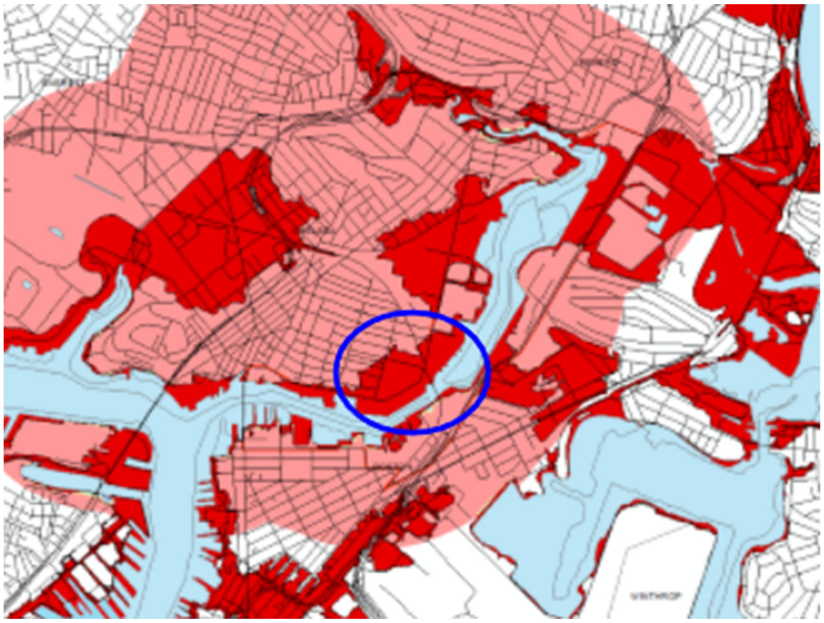


Figure 3. Map illustrating flood projections from FEMA with Marginal Street inside the blue outline. The red shaded areas represent predicted sea rise after a hundred year flood event and the pink shaded areas represent predicted sea level rise after a five hundred year flood event.

The City of Chelsea is at risk to flooding events, with around 50% located in a designated flood plain. Local sea level rise will directly impact the infrastructure of the Marginal Street area through increased flooding events. The United States Geological Survey (USGS) describes substantial flooding events as, “a flood having a 100-year recurrence interval” (USGS, 2018, pp.1). One hundred year floods, despite what the name implies, actually have a 1% chance of occurring each year. Figure 4 illustrates that the mid latitudes experience such weather events at over 200% of the 1970s frequency and the corresponding intensity is 75% higher than 1970 measures (Office of Coastal Management, 2017). Coastal cities need to prepare for these more intense weather events, including both 50 and 100 year flooding events. As such, this Major Qualify Project aimed to provide recommendations for the City of Chelsea to improve their network resiliency.

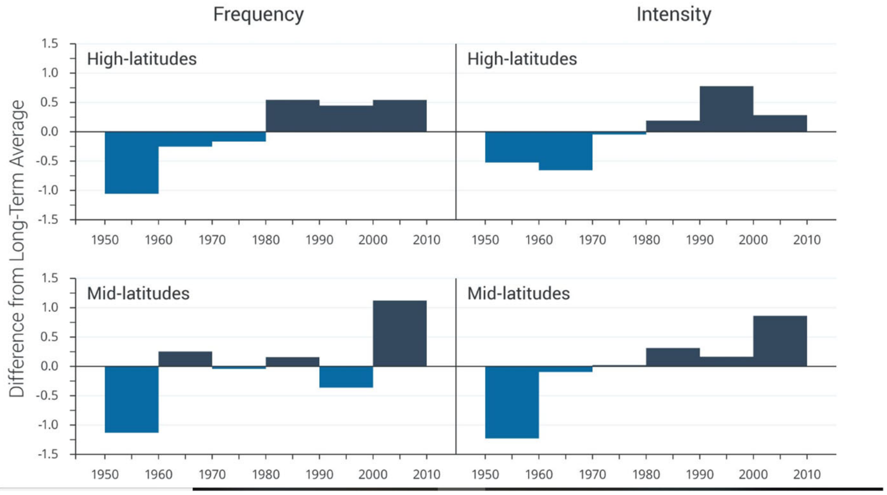


Figure 4. Bar graphs which represent the increased frequency and intensity of weather events over the past 60 years over two latitudinal areas (Office of Coastal Management, 2017)

2.3 Vulnerabilities of Flooding and Severe Storms

Flooding can have a multitude of impacts on natural and built environment including sheet erosion, infrastructure damage, and ecosystem destruction. Sheet erosion, one such effect, can degrade soils and roadways causing landslides, mudslides, and deterioration of paved and unpaved roadways. Structures, such as buildings or bridges, face worse potential damage from long standing floods rather than temporary floods. In either case, damage to infrastructure will directly affect transportation and accessibility within Chelsea. Many popular forms of transportation in the city are affected by flooding like road, rail, and air travel. Some airports, like Boston's Logan International Airport, which is built right on the coast and at sea level, could be susceptible to submerged runways. Railroads, especially in cities near the coast, are vulnerable to flooding because tracks are frequently placed in low or marsh-like areas which could sink or washout from under the tracks (Titus, 2002). Tunnels used by subway systems and roadways as they pass below sea level are vulnerable to flood waters that overcome the flood walls blocking the water from rushing down the tunnel. For example, in New York City recent major storms completely flooded tunnels in lower Manhattan (Titus, 2002). One other risk with flooding above tunnels is the increase in water causes a correlating increase in the hydraulic pressure on the tunnel. Roads are the most vulnerable transportation system to flooding because water causes them to be impassable. Road closure can prevent emergency crews from reaching areas in need and people from evacuating in a timely fashion; therefore, endangering their safety (Titus, 2002).

Cities can evaluate their resilience to flooding and other major weather events to better prepare for and recover from these events. Understanding potential weaknesses within infrastructure can provide insight into specific areas of improvement such as flood resistant structures, evacuation routes, and emergency response systems. The City of Chelsea could benefit from such analysis along the Marginal Street area to effectively and efficiently update and implement such measures.

2.3.1 Flooding and Stormwater Impact on City of Chelsea Infrastructure

The occurrence of flooding damage to structures is dependent on several factors, including "the depth of water in and around the structure, the length of time of inundation, the toxic extent of contaminants in floodwaters, and how rapidly the water is moving" (FEMA, 2011, pp. 18). A flow of water moving at 10 mph exerts the same amount of pressure on a structure as wind gusts of 270 mph and can cause sudden destruction of buildings and roadways. Water that sits in structures for extended periods of time can damage the integrity of the structure, such as wood foundation pilings, structural beams, utilities, and walls." (FEMA, 2011). Chelsea has previously experienced flooding along various roadways, including Marginal Street and is expected to experience increased flooding instances as sea levels rise. The current and potential damage caused by flooding will affect local businesses along Marginal Street. This project will recommend strategic adjustments to the flood preparation and response to mitigate potential consequences.

2.3.2 Flooding and Stormwater Impact on Chelsea's Transportation Networks

Climate change will impact transportation system networks to varying degrees. Sea level rise increases vulnerability of transportation services and directly affects the permissibility of roadways, thereby influencing traffic flow and transport reliability. Flooding and inundation of segments of transportation systems can disrupt connectivity of regions and accessibility within the city (CCSP, 2008). As a result, traffic delays are expected with road closures and detours, straining the transportation systems. These transportation systems are integral to Chelsea's industrial economy and provide important functions to Boston. Along Marginal Street a salt pile is maintained by Eastern Minerals and is utilized in the region during the winter season. Marginal Street also functions as an evacuation route for Boston (Stantec, 2018). Additionally, industrial and commercial buildings are located in the Marginal Street area such as the Boston Logan International Airport parking services that serves hundreds of airport employees and customers. Flooding or failure of infrastructure on Marginal Street will interrupt local traffic, regional accessibility, and the safety of transportation networks.

2.3.3 Importance of Flooding Resilience

Coastal cities will inevitably be faced with storms and natural disasters. A city that is resilient and prepared, socially, financially, naturally and physically will have less trouble recovering from disasters. Being prepared and having a plan to protect the most vulnerable populations can save lives while taking preventative measures can protect result in less damages from storms making it cheaper to recover. One example of preparedness is the use of manmade wetlands such as mangroves that can significantly reduce the impact of storms on both man made infrastructure and the environment. However, failing to prepare for the inevitable storms can be both costly and dangerous to human life.

2.4 Post Flooding Response and Preventative Measures

Longevity of flooding impacts the severity of damage; floods that rise and recede quickly cause less damage than floods when water sits for weeks. Large storms and major hurricanes regularly cause billions of dollars in damages. The most significant recent storms were Hurricane Katrina and Hurricane Harvey. In August of 2005 Hurricane Katrina hit the East Coast, displacing more than a million people and causing 161 billion dollars in damage. Twelve years later, in August of 2017, Hurricane Harvey destroyed 204 thousand homes while causing 125 billion dollars in damage (NCEI, 2018).

The damage from hurricanes and other large storms are not only costly but also displace residents from their homes and can take years to recover to previous infrastructure conditions. Flooding can destroy homes and uproot communities while causing massive amounts of damage. Consequently, the post flood clean up and recovery process requires planning and funding. The City of Chelsea and other coastal cities should enact preventative measure where applicable to reduce the cost of recovery. Many of the solutions to combat flooding are adaptations to existing infrastructure. Ideas such as seawalls, early notifications systems, drainage and retention systems, levees, dikes, and dams are effective methods of reducing the impact of flooding. Communities implementing adaptation methods will find themselves better equipped for floods, and combined with preventative methods will significantly reduce infrastructure damage, and environmental and economic impacts.

2.4.1 Sea Walls

Sea walls can be an effective method of reducing the impact of storm surges; however, they do not come without complications. Seawalls are susceptible to failure from overtopping, and often provide a false sense of security for communities. Specifically, "seawalls smaller than five meters in height appear to have encouraged development in vulnerable areas and exacerbated damage" (Nateghi, 2016, pp. 4). However, Nateghi, an author with the Public Library of Science, points out that "seawalls larger than five meters in height generally have served a protective role in past events, reducing both death rates and the damage rates of residential buildings" (Nateghi, 2016, pp. 4). From this source, it is clear that height is a determining factor in the structural soundness and effectiveness of seawalls. Limitations discussed in the next section reveal that the City of Chelsea has unique circumstances for the type of construction that can happen in the area. Taking these limitations into consideration, a seawall is the most feasible and effective preventative measure.

2.4.2 Drainage/Retention Systems

Urbanization has created the need for new drainage systems, referred to as stormwater management systems. These systems seek to maximize convenience to individual sites by rapidly removing excess surface water after rainfall through a closed conveyance system (FEMA, 2011). While current stormwater management systems do an adequate job managing the storms of today, with rising sea levels and increasing intensity of storms, such systems will be inadequately equipped to handle storm surges in the near future. However, in regards to drainage systems, FEMA notes that "the cumulative effects of such an approach has been a major cause of increased frequency of downstream flooding, often accomplished by diminishing groundwater supplies, as direct results of urbanization" (FEMA, 2011, pp 4). For this reason, this report will not suggest the use of a stormwater retention system to combat flooding in the City of Chelsea.

2.5 Limitations

Any design suggested for the Marginal Street area will be required to observe the rules and regulations of several relevant bodies, including the Massachusetts Port Authority. The area of interest in this project borders waterways which are regulated by Chapter 91 of the Massachusetts State Legislature: Waterways Act. The act was passed in order to control the use of designated port areas, such as the area of interest along Marginal St. This act set regulations for all of the waterways in the state, including Chelsea Creek. It encompasses everything from the duties of local departments of public works and landowners, permitting and zoning, and rules on removal of tidelands.

2.5.1 Designated Port Area

Part of the Chelsea Creek shoreline is designated as a port area, which has special regulations for land use near the water. The satellite image in Figure 5 shows the areas of Chelsea that are designated as a port area between the water and the red line. The area between Marginal Street and the water is in the designated port area meaning that the regulations in the area will need to be considered when proposing solutions for the city.

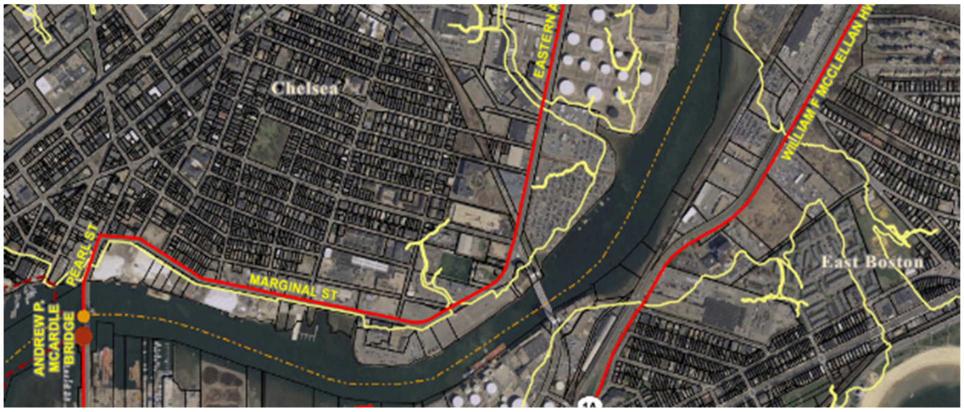


Figure 5. The image shows the Designated Port Area in the City of Chelsea with the red perimeter line (MASSACHUSETTS OFFICE OF COASTAL ZONE MANAGEMENT).

2.5.2 Regulatory Floodways

Regulatory floodways are channels of rivers and other bodies of water which are conserved to ensure that water accumulated from the hundred year base flood can be discharged. The purpose of these designated water bodies is to preliminarily prepare an area for major flooding events. Unfortunately, as seen in Figure 6, the City of Chelsea does not have an impactful number of regulatory floodways.

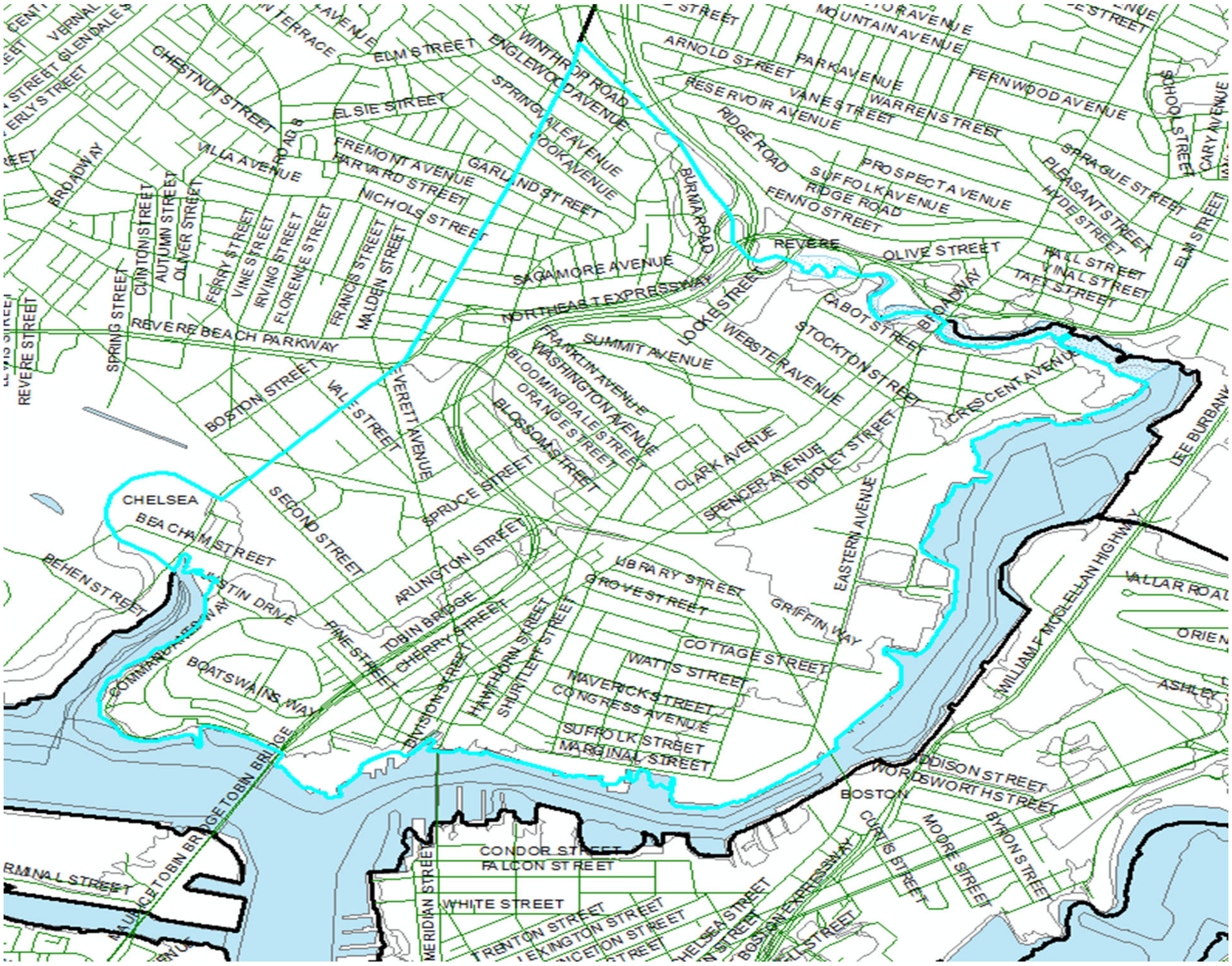


Figure 6. Map shows the Regulatory Floodways in the City of Chelsea at the border of Chelsea and Revere which is an area outside of the project's main area of focus and planned development. The area is marked with small blue dots.

Since there are a low number of regulatory floodways this measure will not prevent the flooding scenarios predicted by FEMA and NOAA. Being aware of the regulatory floodways is important because these areas serve as a place where development is prohibited. Knowing that regulatory floodways do not surround the Marginal Street area means that development of a seawall can happen to protect that sector of the city.

3.0 Objectives and Methodology

To meet our overarching goal of evaluating and improving the transportation resiliency of the Marginal Street area, we created a series of objectives to guide our project. These objectives are presented as follows:

- To assess the flooding resiliency of Chelsea in regards to robustness, redundancy, resourcefulness, and rapidity
- To create flood maps of Chelsea based on climate projections for the year 2030 and 2050, and a 100 year flood map
- To assess the impact flooding will have on common modes of transportation and identify alternative routes.
- To create a design such as a sea wall to combat rising sea levels and increased instances of flooding

Figure 7 demonstrates the logical flow of our project. We analyze the four topics in the second tier of Figure 7 to evaluate the transportation resiliency of Chelsea and provide recommendations for improvement. We used Geographical Information System (GIS) mapping to visualize the flooding impact on the Marginal Street area; this provided context for an analysis of the traffic detouring. In addition, we evaluated different design solutions considering legislative and practical restrictions. In order to reach these objectives, we have outlined a methodology that will allow us to effectively complete our tasks.

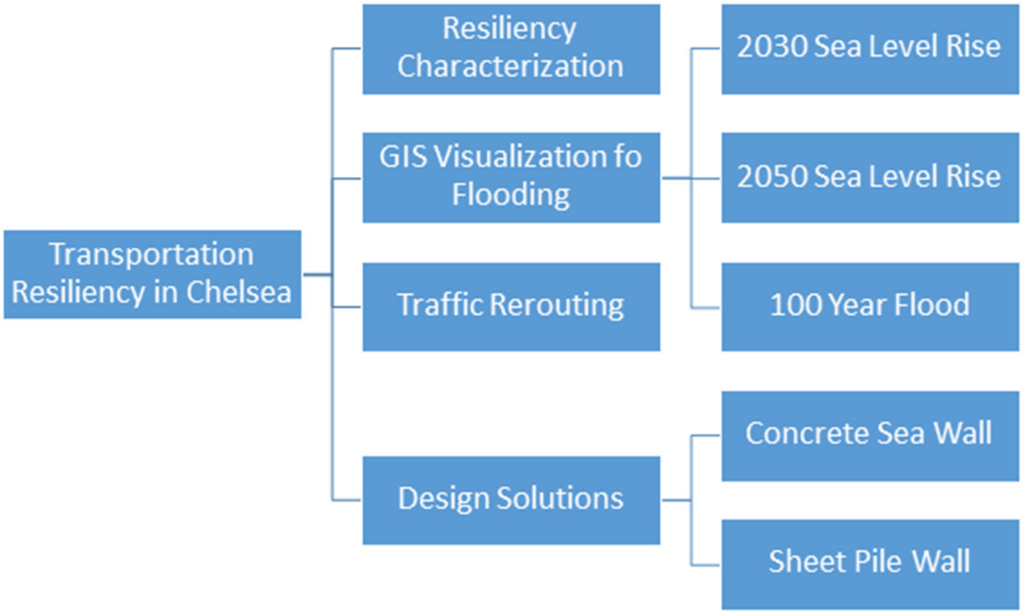


Figure 7. The objectives of the project represented in logical order with hierarchical detail.

3.1 Visualizing Flooding in Chelsea using GIS Software

To assess the impact flooding will have on our area of focus we used GIS to visually represent a variety of different flooding scenarios for the years 2030 and 2050; this includes high tide, storm surges, and annual one percent and 10 percent probability. A 100 year flood map was also presented. This allowed for a comprehensive understanding of the direct impact flooding will have on Marginal Street and the surrounding area in Chelsea.

3.1.1 Creating a Base Map Layer for GIS

To view the layout and orientation of Chelsea and to have a starting foundation for the project, the team used GIS to create a base map of the city. This base map, seen in Figure 8, contains a highlighted Marginal Street, roadways, and waterways. Viewing these features allowed us to make initial predictions about how flooding will affect the city and consider potential solutions. For ease of use, the team altered the color schemes of the initial layers, choosing the hollow color feature when working with outlines to make the base map as simple as possible. The traffic network is displayed in green. This base map was developed to act as a foundation for viewing flooding scenarios and their effects on traffic networks.

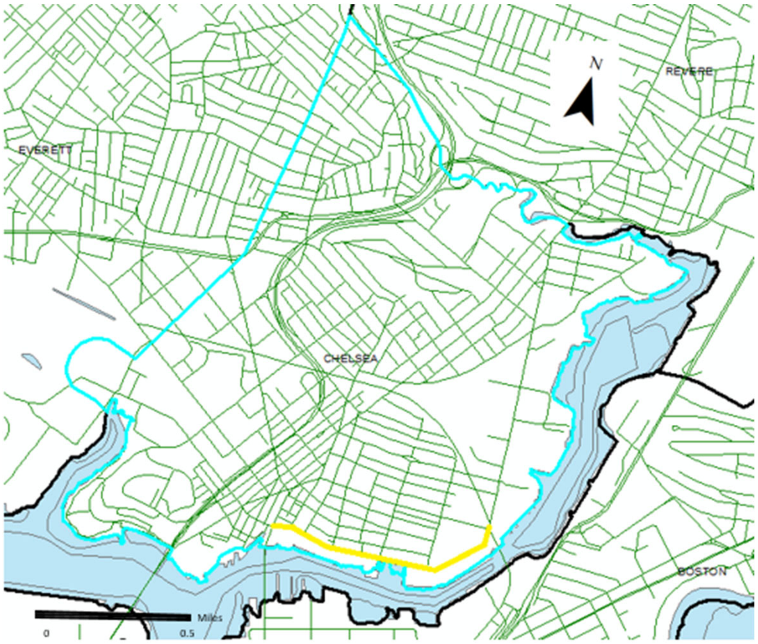


Figure 8. Base Map of the City of Chelsea's Roadways and Waterways. Marginal Street is highlighted in yellow.

3.1.2 Determining and Displaying the Thirty, Fifty, and Hundred Year Flooding Scenarios

In order to understand the conditions the City of Chelsea needs to prepare for over the next century, a series of maps were created using information from external sources in tangent with GIS. A majority of the external information was compiled from the Federal Emergency Management Agency and the National Oceanic and Atmospheric Administration. Both of these organizations have done extensive research to predict flooding scenarios across the United States and share this data with the public.

Superimposing this information onto the GIS base map allowed the team to extrapolate how storms and rising sea levels will affect key areas of the City of Chelsea. To display focused areas in the city, the team used geoprocessing GIS tools to create a shape files which narrowed the view of the maps. The maps for the years 2030 and 2050 were created using the predicted sea level rise from climate change and the monthly average high tide levels. The hundred year flood was viewed without these changes taken into consideration and this scenario acts as a baseline for distant future flooding events. In order to analyze the amount of inundation affecting the city, the GIS clipping tool was utilized to in combination with the geoprocessing tool to find the area where flooding is taking place in each scenario. This process additionally provided the names and number of streets touched by flooding from the monthly average high tide, the one percent, and the ten percent flooding scenarios for the thirty and fifty year flooding scenarios.

For ease of viewing, the team captured snapshots of the maps with specific layers applied to illustrate each predicted scenario. These snapshots focus on the Marginal Street area of Chelsea as this is our main region of focus. Although many of the scenarios result in noteworthy levels of flooding, the changes in flooding represented by shading on the maps can often be difficult to distinguish. To mitigate this perceived issue, the team chose to present the flooding scenario data using brightly colored gradients. Similarly, the features on the map are highlighted as a way to improve visual understand and to reference in our writing and presentation.

3.2 Determining the Best Route to Redirect Traffic during Flooding Events

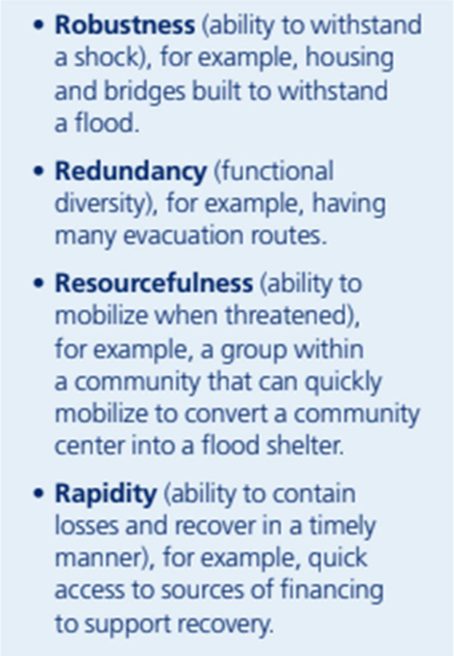
We considered common modes of travel for rerouting traffic such as public transit and the average commuter. We used the maps to identify roads that will be impassible in the event of a 30 or 50 year flood. Roads that remained unaffected by the flood were evaluated to determine their conditions. Using information provided by MassDOT databases we selected roads with similar capacity and size to redirect traffic. Detour routes were selected based on Level of Service (LOS), Average Daily Traffic (ADT), and relative speed limit. The goal of the detour route to provide users with a safer alternative to travel within Chelsea.

3.3 Characterization of Transportation Network in terms of Flooding Resilience

The transportation network as a whole required evaluation to assess the predicted resilience when a flooding event occurs, with a focus along the Marginal Street area. To do this we relied on two academic or professional tools; one was developed by the Multidisciplinary Center for Earthquake Engineering Research and the other, by the UK Department for International Development. The two models were combined into a comprehensive model by Zurich, an international insurance agency. The team applied this comprehensive model to Chelsea to determine how quickly the City of Chelsea and the Marginal Street area could recover from a flood.

3.3.1 Four “R” Model

The Four R Model was developed at the University of Buffalo for earthquakes; however, the model can be applied to other natural and manmade disasters. The four R’s are Robustness, Redundancy, Resourcefulness and Rapidity defined in Figure 3.3. Each aspect of the network is to be assessed by the four R’s to determine the overall resilience of the transportation network. We determined that use of the Four R model alone would be insufficient to capture the complexities of Chelsea’s resilience. To strengthen our analysis, we relied on the analytical model Zurich adapted to include the four Rs and the five Cs.



- **Robustness** (ability to withstand a shock), for example, housing and bridges built to withstand a flood.
- **Redundancy** (functional diversity), for example, having many evacuation routes.
- **Resourcefulness** (ability to mobilize when threatened), for example, a group within a community that can quickly mobilize to convert a community center into a flood shelter.
- **Rapidity** (ability to contain losses and recover in a timely manner), for example, quick access to sources of financing to support recovery.

Figure 9. The Four Rsof Resilience

3.3.2 Four “R” / Five “C” Model

The Five “C” Model combines with the Four “R” Model to form a more in depth system to determine the resilience of a transportation network. Each capital or “C” represents an aspect of the specific community or network that can be measured using the four R’s. The five capitals are Human, Social, Physical, Natural, and Financial as shown in Figure 10.

- **Human** (education, skills, health).
- **Social** (social relationships and networks, bonds that promote cooperation, links facilitating exchange of and access to ideas and resources).
- **Physical** (things produced by economic activity from other capital, such as infrastructure, equipment, improvements in crops, livestock).
- **Natural** (natural resource base, including land productivity and actions to sustain it, as well as water and other resources that sustain livelihoods).
- **Financial** (level, variability, and diversity of income sources and access to other financial resources that contribute to wealth).

Figure 10. The Five Capitals

Once each capital was broken down into the four R's it was given a grade from A-D, depending on how they meet the criteria. Figure 11 represents the grading scale for each of these capitals. Using this scale we were able to determine the overall resilience of the transportation network of Chelsea to flooding.

- **A:** Best practice for managing the risk.
- **B:** Good industry standard, no immediate need for improvement.
- **C:** Deficiencies, room for visible improvement.
- **D:** Significantly below good standard, potential for imminent loss.

Figure 11. Grading Scale for the Five Cs

3.4 Creating a Design

A critical portion of increasing the City of Chelsea's resiliency along Marginal Street will be to protect Marginal Street from the projected effects of climate change. Our final objective is to create a design component to combat rising sea levels and increased instances of flooding. To do so, we investigated various designs intended to combat sea level rise and flooding. To make a selection, we compared the feasibility of each design to the relevant Port Authority regulations and the limitations of the selected location. After making a selection of designs to compare, we performed calculations to determine the dimensions of the wall and verify the soil would accommodate the design. To verify these, we input the design parameters into the 3D Design Analysis Risa 3D. With our loading calculations confirmed, we modeled the design in AutoCAD 3D.

3.4.1 Evaluating Alternative Design Solutions

To select various designs to evaluate for use along the Marginal Street corridor, we researched the most common installments along coasts to protect against rising sea levels and erosion. We then cross referenced the necessary parameters of these designs against the parameters of our project. We eliminated designs that required backfill, as Port Authority Regulations require any design component to be built along the pedestrian walkway on Marginal Street, set back from the shoreline. Additionally, we eliminated designs that could not accommodate the projected maximum thirty year sea level rise plus flooding. Finally, we selected from the remaining options based on simplicity and feasibility, given the number of assumptions required for our calculations. Our analysis lead us to select the Concrete Block Design and Sheet Piling Design for comparison.

3.4.2 Concrete Block Design for 2030 Scenario

The initial design for a ten year wall design is intended to serve as an additional installation which can later be built expanded to accommodate future sea level rise. This design includes stacking only one concrete block with a cap, secure by drilling and grouting rebar. The initial 2.5 foot structure depth along the Marginal Street side was calculated using the profile elevation and the base cross section width, assuming no beach structure in front of the base on the Chelsea Creek side. Based on tide and wave data from US Harbors, the initial design wave height was 1.8 feet, assumed to be two feet for a factor of safety (US Harbors, 2018). We based the design water level off the maximum water elevation for 2030 sea level rise and a 100 year flood scenario.

We began by calculating the weight and normal forces per linear foot in a concrete structure of those dimensions, assuming the weight of concrete to be 150 lbs. per cubic foot. Next, we calculated friction using the internal angle of friction, assumed for the soil type to be 35° based on Stantec boring logs. Using this information from the soil, we looked at the bearing capacity of the soil to ensure it would not fail. We used Prandtl's equation for ultimate bearing capacity for structures at the surface of a soil. Then we performed two sets of calculations to cover two circumstances: one for low water and the other for the design water level and wave height.

3.4.2.1 Case 1: Low Water

For Case 1, low water, we assumed that gravity, earth forces, reactive forces, and friction would act on the structure. The weight, equivalent normal forces in the absence of other vertical forces, and friction remain the same in both cases. Using the Stantec boring logs to determine the physical properties of the soil along Marginal Street, a unit weight of 97 lbs. per cubic foot is assumed for the earth force calculations. There are several methods which can be used to calculate earth pressure and surface fail, the two most prominent being the Rankine and Coulomb Methods. We elected to use the Rankine method, which is considered the more conservative of the two in regards to surface failure (Soon, Salman, & Shirazi, 2012). We calculated the active earth pressure from the internal angle of friction in this method with this information we calculated the earth forces. In this case, the earth force serves as the anti-stabilizing force and friction is the stabilizing force to resist sliding. Calculating the moments generated by these forces, we were able to calculate the factor of safety for this scenario and determine the suitability of the structure in these conditions.

3.4.2.2 Case 2: Design Water Level and Wave Height

In Case 2, we assumed gravity, earth forces, normal reactive forces, friction, wave uplifts, hydrostatic forces, and horizontal wave forces act upon the structure. The weight is assumed to be the same in this case as in the previous one. In this case, to calculate forces due to waves, we relied on the method described in the United States Army Corps of Engineers' Coastal Engineering Manual. There are few consistent guidelines for determining design wave loads. The calculations need to be consistent with American Society of Civil Engineer (ASCE) guidelines and FEMA guidelines for coastal structures (Wiebe, Park, and Cox, 2013). To meet these requirements, wave forces were calculated based on the Goda Formula, which is one of the most widely accepted methods for calculating wave forces. The Goda Formula clarifies the concept of uplift pressure on the bottom of a vertical wall; the buoyancy of the section still in water and the uplift pressure due to wave action are defined separately; however, the Goda-Takahashi formula, an expansion of the Goda formula that allows for more specific modifications, combines these forces into a single uplift calculation as represented in Figure 12.

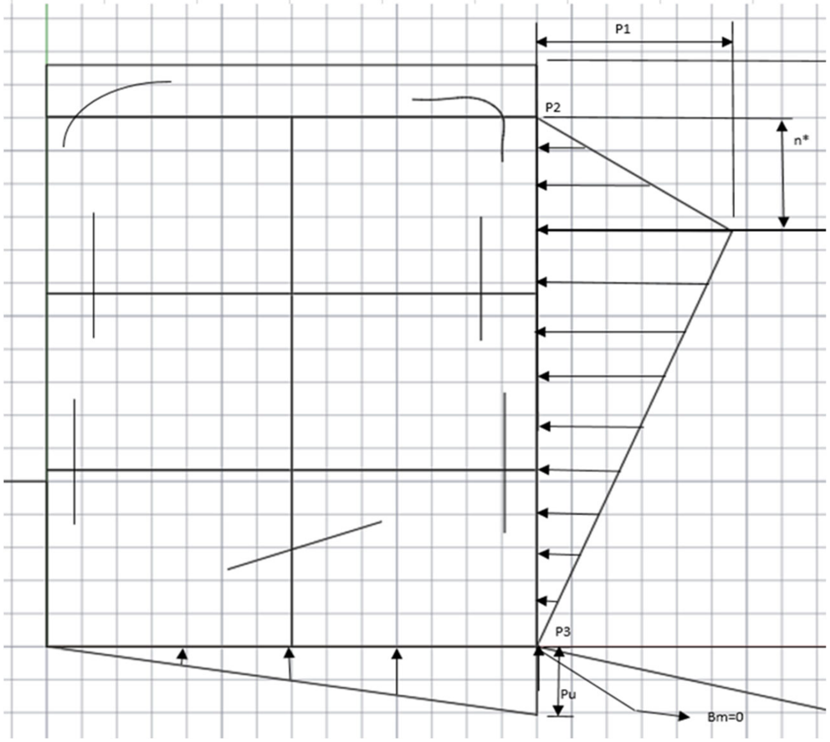


Figure 12. Distribution of Pressure Forces on a Vertical Sea Wall

The formula assumes a trapezoidal pressure distribution and predicts the maximum pressure at a design water level, assuming the pressure decreases linearly to the depth and height of the structure when modified for irregular waves. (Wiebe, Park, and Cox, 2013). We further modified the formula to include impulsive forces and to the geometry of our proposed design, as described in the manual, which makes use of the extended formula, the Goda-Takahashi formula. We excluded a rubble foundation to simplify calculations.

This method was used to calculate the free surface height, wave pressures at different elevations on the structure, and the wave uplift. Then, the Rankine Method was used again to calculate the passive earth pressure and the resulting earth force. In this case, the anti-stabilizing forces are equal to the sum of the wave and hydrostatic forces and the stabilizing forces are equal to the sum of the friction and earth forces. The moments generated by these forces were used to calculate a factor of safety against sliding.

Finally, to determine the factor of safety against overturning, we calculated the total moments around the toe of the structure. The resultant normal force is calculated to be the difference between the weight and the combined buoyancy and wave uplift force. Depending on the moment rotation, the moments were classified as anti-stabilizing or stabilizing. The total opposing moments are then compared to get the factor of safety.

3.4.3 Concrete Block Design for 2050 Scenario

To determine the initial design case, we relied on the Naval Coastal Design Manual and the Handbook of Coastal and Ocean Engineering to determine how to stack the concrete blocks. Although, the city could elect to use the 2030 design and add on later, these calculation assume the structure is built in its entirety for thoroughness. The USACE recommends stacking blocks no more than two wide and three high. We selected from the Massachusetts DOT standard block sizes to best accommodate our structure design height and design water level for both scenarios. The initial 2.5 foot structure depth along the Marginal Street side was calculated using the profile elevation and the base cross section width, assuming no beach structure in front of the base on the Chelsea Creek side. Just as in the 2030 design case, we relied on tide and wave data from US Harbors, the initial design wave height was 1.8 feet, assumed to be two feet for a factor of safety (US Harbors, 2018). This design water level was based on the maximum water elevation for 2050 sea level rise and a 100 year flood scenario.

The process is the same as was used for the 2030 design scenario. We calculated the weight and normal forces per linear foot in a concrete structure of those dimensions, assuming the weight of concrete to be 150 lbs. per cubic foot. Next, we calculated friction using the internal angle of friction, assumed for the soil type to be 35° based on Stantec boring logs. We used this soil information to test the bearing strength of the soil to ensure it would not fail. We used Prandtl's equation for ultimate bearing capacity for structures at the surface of a soil. Then we performed two sets of calculations to cover two circumstances: one for low water and the other for the design water level and wave height.

3.4.3.1 Case 1: Low Water

For Case 1, low water, we assumed that gravity, earth forces, reactive forces, and friction would act on the structure. The weight, equivalent normal forces in the absence of other vertical forces, and friction remain the same in both cases. Using the Stantec boring logs to determine the physical properties of the soil along Marginal Street, a unit weight of 97 lbs. per cubic foot is assumed for the earth force calculations. We calculated the active earth pressure from the internal angle of friction using the Rankine Method. With this information we calculated the earth forces. In this case, the earth force serves as the anti-stabilizing force and friction is the stabilizing force to resist sliding. Calculating the moments generated by these forces, we were able to calculate the factor of safety for this scenario and determine the suitability of the structure in these conditions.

3.4.3.2 Case 2: Design Water Level and Wave Height

In Case 2, we assumed gravity, earth forces, normal reactive forces, friction, wave uplifts, hydrostatic forces, and horizontal wave forces act upon the structure. The weight and friction are assumed to be the same in this case as in the previous one. In this case, to calculate forces due to waves, we relied on the method described in the United States Army Corps of Engineers' Coastal Engineering Manual. Wave forces were calculated based on the Goda Formula. This formula is used for irregular waves. We further modified the formula to include impulsive forces and to the geometry of our proposed design, as described in the manual. We excluded a rubble foundation to simplify calculations.

This method was used to calculate the free surface height, wave pressures at different elevations on the structure, and the wave uplift. Then, the Rankine Method was used again to calculate the passive earth pressure and the resulting earth force. In this case, the anti-stabilizing forces are equal to the sum of the wave and hydrostatic forces and the stabilizing forces are equal to the sum of the friction and earth forces. The moments generated by these forces were used to calculate a factor of safety against sliding.

Finally, to determine the factor of safety against overturning, we calculated the total moments around the toe of the structure. The resultant normal force is calculated to be the difference between the weight and the total uplift force. Depending on the moment rotation, the moments were classified as anti-stabilizing or stabilizing. The total opposing moments are then compared to get the factor of safety.

3.4.4 Software Loading Applications

After completing these calculations, we built the design parameters and all calculated forces into Risa 3D to confirm our calculations. In order to avoid any potential errors in the software, this process was repeated three times to achieve identical results. The software did not contradict the results of our manual calculations, so we proceeded to model the design.

3.4.5 Software Modeling Applications

Following the satisfactory completion of the seawall design, we modeled both concrete structures structure in AutoCAD. This involved extruding the cross sectional design along the proposed path on Marginal Street, from Broadway Street to the Chelsea Street Bridge. This model assumed the elevation to be uniform along Marginal Street, to be consistent with our calculations.

3.4.6 Sheet Pile Wall Design

We also picked a sheet pile wall to be evaluated and designed for use along Marginal Street. The active earth pressure from the internal angle of friction had been calculated using the Rankine Method. Sheet pile walls are most common in temporary use, however, we chose to evaluate it as an option. We chose a cantilever sheet pile wall for our design because this design does not require backfill and since we have to construct the wall along the street, there is no room for backfill. We used the Rankine Method to calculate the soil pressures and the depth to which we would drive the piles.

3.4.7 Cost Estimates

We prepared a basic cost estimate for all design solutions we looked at. These cost estimates used material costs and basic production rates and labor costs to provide a rough concept of the cost to complete construction. Estimates of this kind are typically considered to have accuracy of -50%-100% (Salazar, 2017). The material costs were an average of three material costs from major suppliers, sourced from their websites. The production rates were from New York and Wisconsin State DOTs to establish construction standards. These standards dictate crew size. The labor rates are Massachusetts' prevailing wage rates.

4.0 Results

The goal of this project was to assess and reduce the impacts of flooding on transportation resiliency in the City of Chelsea, Massachusetts. This chapter presents and analyzes the results of this Major Qualifying Project; these results include GIS visualization of flooding in the city, analysis of the impact on traffic, characterization of the network resilience, and design analysis of multiple sea wall structures.

4.1 Creating Base Map Layers in GIS for Visualization of Flooding

To visualize the impact of each flooding scenario on the traffic network in the City of Chelsea, a base map can be viewed in Figure 13. Chelsea is within the highlighted, bright blue area and the surrounding towns of Everett and Revere fall outside of the perimeter. The lighter blue area surrounding the city on the east and south sides are the Mystic River and the Chelsea Creek. The green lines on the map depict the traffic network. The base map seen in Figure 13 omits the impacts of flooding or storms. The bottom of the map, highlighted in yellow, is the area of interest for this project. Marginal Street is a key roadway in the city and losing the street to flooding will have major effects on the overall traffic network.

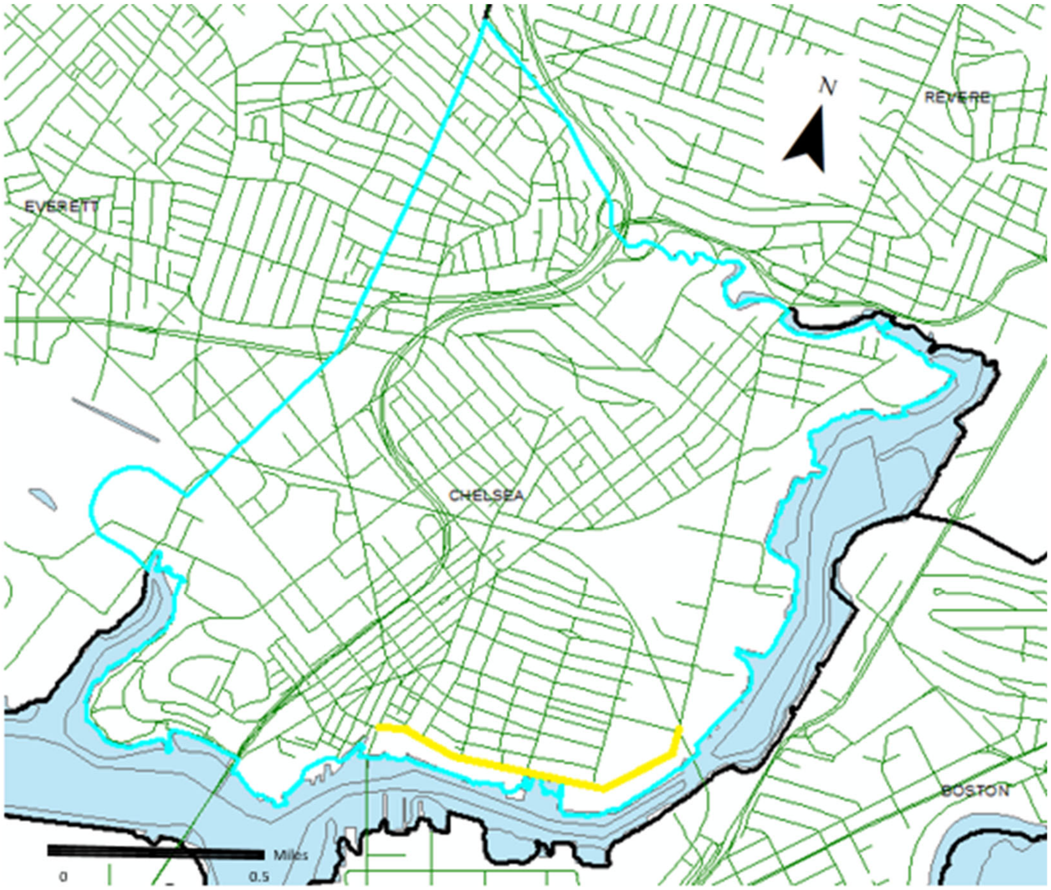


Figure 13. Base Map of the City of Chelsea's Roadways and Waterways. Marginal Street is highlighted in yellow.

4.2 Displaying Flood Scenarios using GIS

Three flooding scenarios were investigated using GIS to determine affected and vulnerable areas. These flooding scenarios are dependent on predicted sea level rise. The first flood scenario encompasses potential flooding for the year 2030 with considerations for high tide, flooding events with ten percent likelihood, and flooding events with one percent likelihood. The second flood scenario is based on predicted flooding for the year 2050 with the same considerations modified for additional climate changes. The third scenario is a hundred year flood scenario with base flood elevation taken into consideration. High tide, one and ten percent chance flood occurrences were not taken into consideration for the hundred year flooding scenario. To present the city with a reasonable deliverable, climate change effects in 2030 and 2050 were thoroughly considered. The high tide scenario for the years 2030 and 2050 take into account the monthly high tide average. The monthly high tide average is the highest tide from each month averaged together (Analyze Boston, 2016). The monthly average is approximately two feet greater than the daily high tide and results in a more accurate and extreme scenario. The one and ten percent chance flooding events are based on the predicted storm surge and sea level rise conditions for the years 2030 and 2050 respectively.

4.2.1 Flooding Scenario 1 - 2030

The flooding scenarios in 2030 were examined under three different conditions based on a prediction of 9 inches of sea level rise for the given year. The following maps display the extent of flooding occurrences due to high tide, ten percent likelihood of occurring, and one percent likelihood of occurring for a thirty year event. The high tide scenario is seen in Figure 14 where the shaded orange area above the lowest blue line represents the flooding which is likely to occur.

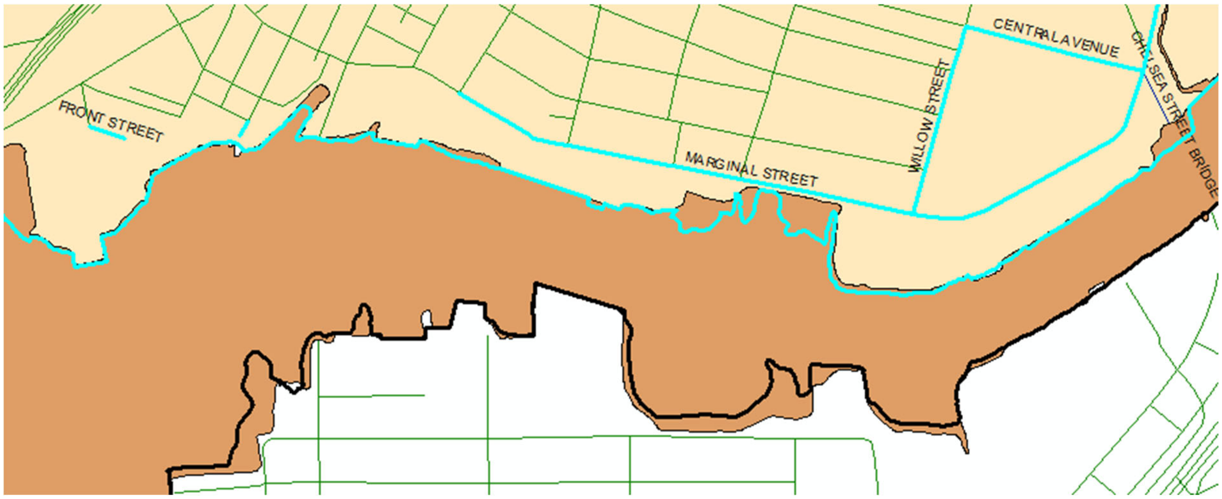


Figure 14. Map illustrating the flooding effects of average monthly high tide in the year 2030 on the Marginal Street area

In this scenario, Marginal Street is predicted to endure minor flooding. The 9 inch rise in sea level alone will not cause substantial flooding. A total of 0.24 miles of Chelsea roadways will be inundated in this scenario. The affected roadways are listed in Table 1. In 2030, the only affected roadway will be the Tobin Bridge Connector. The Tobin Bridge connects Chelsea to Charlestown, which is a heavily used roadways with 77,685 ADT in 2012. The closing of this connector will affect traffic in the surrounding area of Chelsea and Charlestown, creating an increase in vehicle density and decrease in flow rate. If the connector becomes impassible, users will have to find an alternative route in order to arrive at their destination.

Table 1: 9 Inch Sea Level Rise High Tide

Streets Within Flooded Area
Tobin Bridge Connector
Total Miles: 0.24

There is a substantial risk of flooding in the focus area during storm events. The storm events examined are the one hundred and ten year storm predictions for the year 2030. The ten percent storm event's flooding potential is shown in pink in Figure 15. Flooding along the Marginal Street area is shown above the lowest blue line, which represents the shoreline.

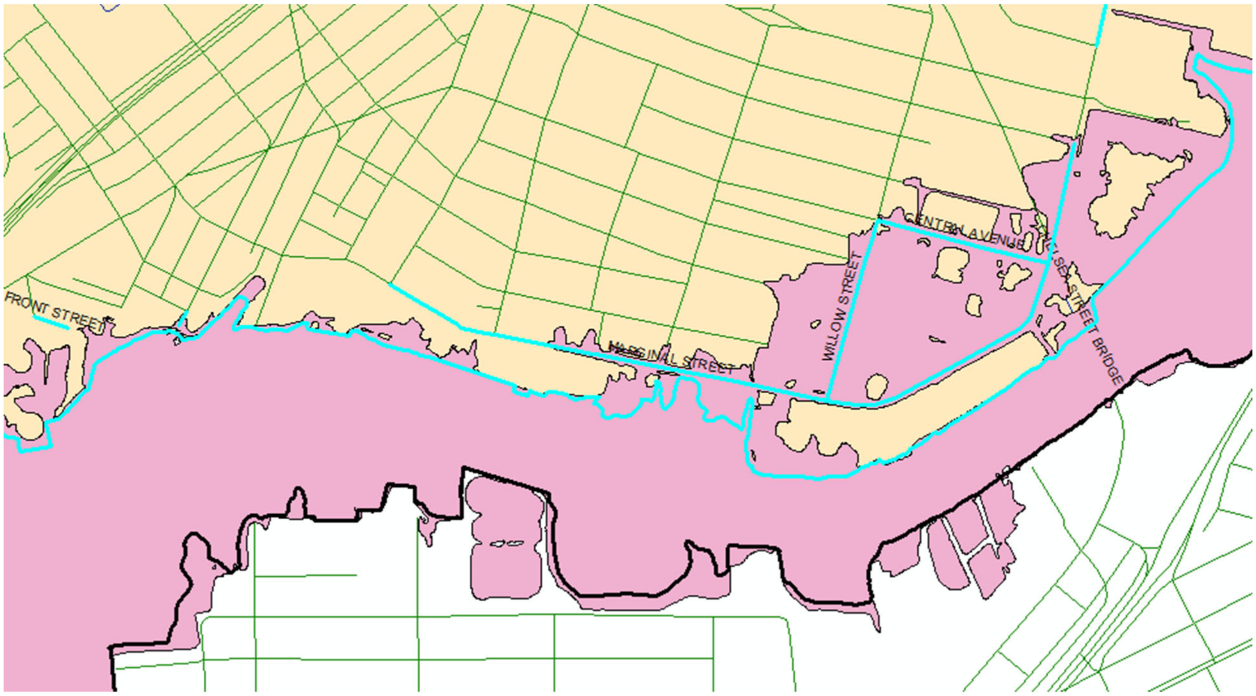


Figure 15. Map illustrating the flooding effects of a ten year flood under the conditions of the year 2030 on the Marginal Street area

A ten year storm has a ten percent chance of occurring within any given year. Figure 15 illustrates a ten year storm's flooding extent based on the conditions estimated for the year 2030. For the City of Chelsea, eight roads will fall within the flood zone and approximately 2.27 miles of the road segments in Chelsea would be inundated in this scenario. Many of these roads will become impassable and be closed off, or will greatly reduce speed in which vehicles normally travel the roadways therefore affecting the flow rate of affected roads. The roads that are affected are listed in Table 2.

Table 2: 9 Inch Sea Level Rise 10% Annual Flood

Streets Within Flooded Area	Miles Flooded
Marginal Street	0.53
Eastern Avenue	0.49
Willoughby Street	0.11
Crescent Avenue	0.31
Willow Street	0.15
Tobin Bridge	0.24
Parker Street	0.06
Vila Street	0.03
Total Miles:	**1.92**

The 100 year storm has a 1% chance of occurring in any given year. The flooding projections from this 100 year storm in 2030 can be found in Figure 15 with the flooding shown in yellow. In this map, the flooding above the lowest blue line affects portions of Marginal Street, Willow Street, and Chelsea Street; other roads in the city are affected, but not shown in this Figure 16. A series of connected roads will block accessibility to certain businesses and services established along Marginal Street and surrounding area. Transit and accessibility to public transportation will be severely limited in this instance. A more thorough interdisciplinary analysis of floods impact on Chelsea's transportation network is detailed in section 4.3.

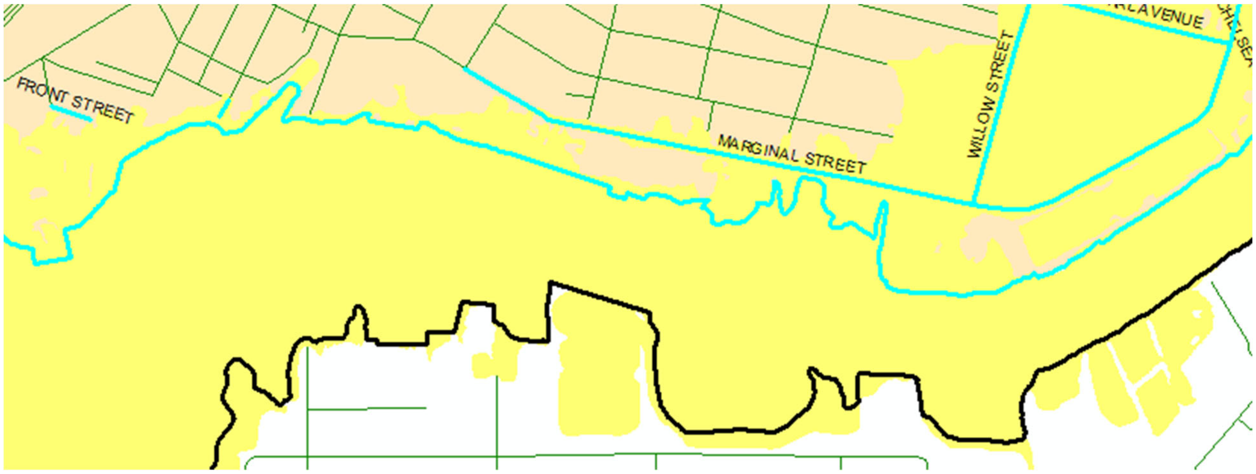


Figure 16. Map illustrating the flooding effects of a one hundred year flood under the conditions of the year 2030 on the Marginal Street area

Although this storm is the model with the lowest frequency included in our analysis, the impact is the most severe. A greater area of the city's topography will be under flood waters in this event, causing the largest impact on the transportation system of the three scenarios for 2030. A total of 3.34 miles of Chelsea's roadways will be inundated under this scenario. All of the affected streets are listed in Table 3

Table 3: 9 Inch Sea Level Rise 1% Annual Flood

Streets Within Flooded Area	Miles Flooded
Marginal Street	0.64
Central Avenue	0.18
Eastern Avenue	0.66
Willoughby Street	0.11
Willow Street	0.15
Winnisimmet Street	0.02
Tobin Bridge	0.24
Spencer Avenue	0.1
Parker Street	0.06
Eleanor Street	0.08
Vila Street	0.03
Total Miles:	**2.43**

4.2.2 Flooding Scenario 2 - 2050

The second flooding scenario we looked at was for the year 2050 and is expected to have a sea level rise of 21 inches. Similar to the year 2030 flooding scenario, the 50 year flooding scenario was also viewed under the conditions of average monthly high tide and ten and one percent chance storm events. All three scenarios analyzed for 2030 were also applied to the 2050 map projections to better understand the extent of inundations that will potentially affect Chelsea. The average monthly high tide related to flooding for the year 2050 can be seen in Figure 17 and is illustrated in the color gray.

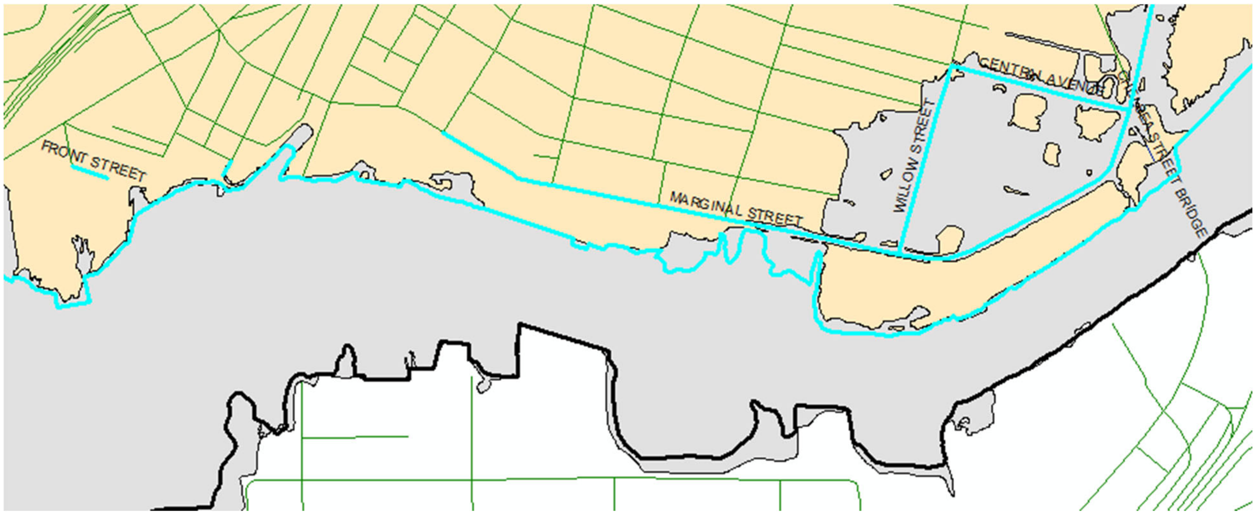


Figure 17. Map illustrating the flooding effects of the average monthly high tide flooding scenario under the conditions of the year 2050 on the Marginal Street area

This scenario would inundate 1.52 miles of the city's roadways and would affect eight streets in Chelsea. Based on the topographical map in Appendix O, the roads submerged in the flooded area fall within 25 feet above sea level. A water depth of six inches or more can reach the bottom of vehicles passing by, causing loss of control and hazardous road conditions. Vehicles passing through inundated roads can potentially hydroplane and cause traffic due to unsafe driving conditions and reduction of travel speed. These streets are listed in Table 4.

Table 4: 21 Inch Sea Level Rise High Tide

Streets Within Flooded Area	Miles Flooded
Willoughby Street	0.11
Crescent Avenue	0.31
Eastern Avenue	0.36
Willow Street	0.15
Tobin Bridge	0.24
Parker Street	0.06
Vila Street	0.03
Total Miles: 1.26	**1.26**

The ten year floods adapted for 2050 can be seen in Figure 18 and are shown in green. The figure shows that Willow Street, Central Avenue, and Marginal Street are inundated in this scenario; other additional roadways not pictured will also be flooded in this scenario.

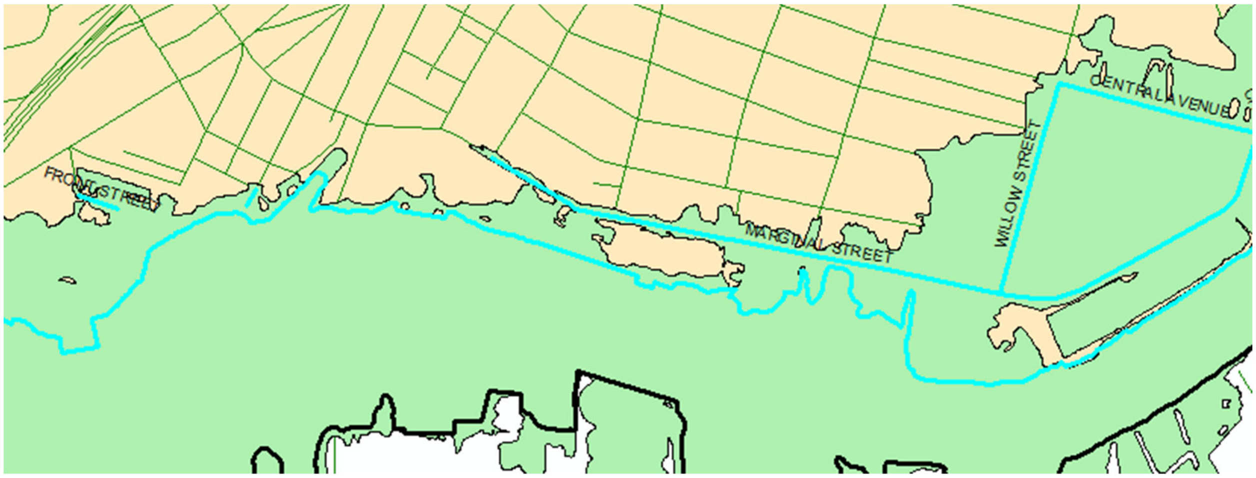


Figure 18. Map illustrating the flooding effects of a ten year flood under the conditions of the year 2050 on the Marginal Street area

The total inundation for the city of Chelsea under this scenario is 3.58 miles of roadway, distributed unequally over 13 streets. These streets are listed in Table 5.

Table 5: 21 Inch Sea Level Rise 10% Annual Flood

Streets Within Flooded Area	Miles Flooded
Marginal Street	0.76
Central Avenue	0.18
Eastern Avenue	0.66
Willoughby Street	0.11
Crescent Ave	0.31
Willow Street	0.13
Winnisimmet Street	0.02
Tobin Bridge	0.24
Spencer Avenue	0.1
Parker Street	0.06
Eleanor Street	0.08
Vila Street	0.03
Front Street	0.03
Total Miles: 2.71	**2.71**

For the conditions estimated for 2050, the 100-year flood (i.e. a flood with a one percent chance of occurring in a given year) can be seen in Figure 19 and is shown with a gray striped gradient fill. This flood covers the majority of our area of focus. Flooding will not be uniform in the affected area, Chelsea's elevation will influence the depth of inundation varying among the roads affected. However, several roads that become impassable will break connections within the transit network, rendering transportation either inefficient or impossible.

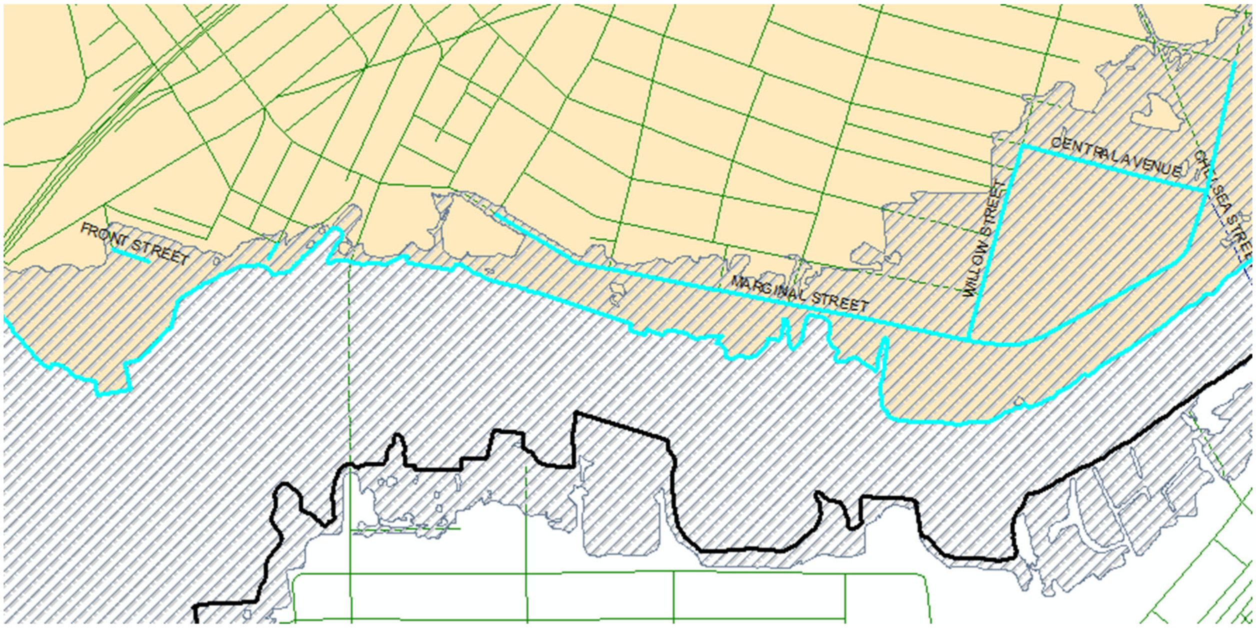


Figure 19. Map illustrating the flooding effects of a one year flood under the conditions of the year 2030 on the Marginal Street area

This is the most extreme example out of the six flooding scenarios presented for either 2030 or 2050; therefore, this scenario represents the greatest inconveniences for transportation throughout the city. This scenario would inundate 4.06 miles of Chelsea's roadways and affect 14 streets in the city. The affected streets are listed in Table 6.

Table 6: 21 Inch Sea Level Rise 1% Annual Flood

Streets Within Flooded Area	Miles Flooded
Marginal Street	0.76
Eastern Avenue	0.76
Central Avenue	0.18
Willoughby Street	0.11
Crescent Avenue	0.31
Willow Street	0.17
Winnisimmet Street	0.2
Spencer Street	0.1
Parker Street	0.06
Eleanor Street	0.08
Vila Street	0.03
Front Street	0.03
Watts Street	0.03
Tobin Bridge	0.24
Total Miles: 3.06	**3.06**

4.2.3 Flooding Scenario 3 - 100 Year

The third scenario seen in Figure 20 was created from data provided by FEMA. The orange gradient fill shows the effects of a hundred year flood assuming conditions with a base flood elevation (BFE). A base flood elevation is the computed elevation to which floodwater is anticipated to rise during the base flood. The base flood is the hundred year flooding event (FEMA, 2014). The FEMA map does not account for climate change; the scenario depicted shows a flood with a one percent chance of occurring in the current year. FEMA denotes this scenario as AE which describes the presence of a base flood. The full descriptions of FEMA flooding designations are provided in Appendix C.

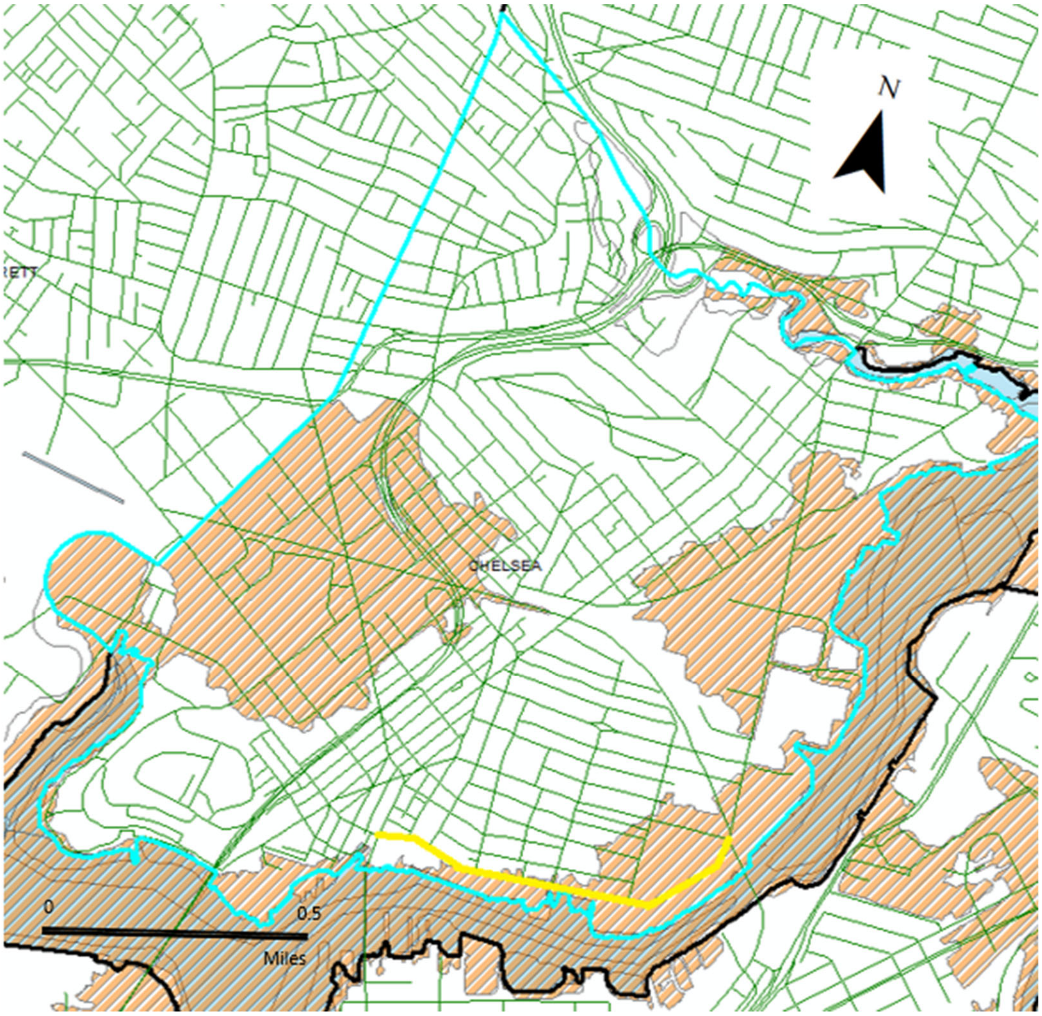


Figure 20. Map Illustrating the Results of Flooding caused by the Hundred Year Annual Flood on the city of Chelsea. Marginal Street is highlighted in yellow.

In this scenario, 10.95 total miles of roadway will be underwater and impassable. The 38 streets that are included in the total mileage of flooded roadway are listed in Table 7.

Table 7: FEMA 100 Year Annual Flood

Streets Within Flooded Area	Miles Flooded	Streets Within Flooded Area	Miles Flooded
Marginal Street	0.64	Central Avenue	0.18
Eastern Avenue	0.67	Willoughby Street	0.11
Revere Beach Parkway	0.55	Maple Street	0.13
Everett Avenue	0.53	Sixth Street	0.25
Spruce Street	0.51	Blossom Street	0.12
Carter Street	0.48	Beacham Street	0.41
Beech Street	0.26	Second Street	0.48
Arlington Street	0.55	Third Street	0.1
Market Street	0.1	Vale Street	0.27
Forth Street	0.23	Exeter Street	0.03
Guam Road	0.05	Auburn Street	0.12
Willow Street	0.17	Tobin Bridge	0.24
Winnisimmet Street	0.02	Parkway Court	0.7
Parker Street	0.06	Fifth Street	0.07
Locke Street	0.08	Bryson Road	0.04
Vila Street	0.03	Front Street	0.03
Williams Street	0.11	Broadway	0.07
Chelsea Street Bridge	0.11		
Total Miles: 10.95			**10.95**

4.3 Transportation Network Analysis

During flooding events, certain roads will be rendered unsafe and impassible. This will impact the accessibility and operations of businesses and service providers. Each GIS flooding scenario has a corresponding list of streets that will be affected, as explained in the three flooding scenarios we modeled in GIS.

4.3.1 Transit Scenarios

The following transit scenarios, in Table 8, will be analyzed for each of the flooding scenarios. These scenarios were chosen based on common modes of travel and users' dependency on specific transit networks. Maps highlighting these modes of transit are included in Appendix C.

Table 8: Modes of Travel

Mode of Travel	Description
Daily Commuter/Passenger	Refers to the daily commuter using main roads in Chelsea. Specifically, this scenario includes destination to Marginal Street area.
MBTA Silver Line 3	Public transit route traveling through Chelsea and East Boston to Logan Airport, Seaport District, and South Station.
MBTA Commuter Rail	This is the line that goes through Chelsea from North Station towards Newburyport and Rockport.

4.3.2 Transit Network Analysis

The year 2050 flooding scenario will greatly impact Marginal Street and those who rely daily on this area to commute. We found that commuters will need to seek out alternate routes by way of Revere; major roadways further inland will not be affected the same way and can also be considered for alternate routes.

Silver Line - Year 2050 Flood:

Flooding caused by the year 2050 storm will compromise the Eastern Avenue MBTA Silver Line station, shown in Map 3 in Appendix D. As a result, the line will need to be rerouted after the Box District Station in central Chelsea. The Silver Line is a bus system and is easier to redirect than a train route. We suggest that the line be rerouted down Broadway Street and out of the city using the Tobin Bridge. From the Tobin Bridge, the Silver Line can reconnect with the Airport MBTA stop in East Boston. This stop is an existing Silver Line stop and is located outside of the Boston Logan International Airport.

Commuter Rail - Year 2050 Flood:

The Commuter Rail is a train and rerouting is more disruptive and less feasible. The fifty year flooding scenario impacts about a half mile of the Commuter Rail line in Chelsea; however, moving this section of tracks further into Chelsea would interfere with existing traffic patterns and residential areas. An alternative to relocating the tracks would implementing a shuttle bus system at the Bellingham Square Station in Chelsea. The buses could travel north on Broadway Street to the Salem Turnpike, bringing passengers to the River Works Station in Lynn and avoiding the inundation.

The third flood scenario is described in Section 4.2.3. A map of this flood map layer and public transit scenarios can be found in Appendix D. These maps illustrate the intersection between the route taken by public transit as defined in Figure 19, and 100 year flood. The following subcategories aim to explain the impact flooding will have on the user depending on mode of travel shown in Map 4 in Appendix D.

We found daily commuters or users traveling in their own vehicle on Marginal Street to cross the Chelsea Street Bridge towards East Boston and Logan Airport will have to find alternative routes. Places like the Preflight Airport parking on Eastern Avenue will be rendered inaccessible through Chelsea therefore affecting Logan Airport workers and flyers. In addition, travel to and from Boston through Williams and Pearl Street will not be possible.

Silver Line - 100 Year Flood:

The Silver Line 3 of Chelsea utilizes bus lanes for faster service. However, using 100 year flood maps we project that these travel routes will be blocked. Appendix D shows the Silver Line superimposed on the flood map. The Silver Line connects to many other bus routes within

Chelsea; all of these route must be reconsidered. We suggests the city implements the same solution here as recommended for flooding scenario one.

Commuter Rail - 100 Year Flood:

The Commuter Rail network will be flooded, and thereby will be unable to be rerouted. No alternatives can be done without major reconstruction on the MBTA rail transit line. Delays and closings are to be expected. People who rely on these modes of transit will have to be accommodated through additional MBTA public bus routes to get to Newburyport and Rockport destinations from Chelsea.

The aforementioned sea level rise scenarios each impact the extent of flooding within Chelsea. Flooding will impact not only transit routes but also accessibility to businesses and services, therefore affecting the local economy. Our focused analyses are included in a nine inch sea level rise as estimated for 2030 and the 21-inch sea level rise as estimated for 2050; the predicted scenarios will affect businesses in this area to varying degrees. Tables 9 and 10 list the businesses affected for both flooding scenario projections.

Table 9: Businesses Affected in 2030- 9 inch Sea Level Rise and flood with a 10% Exceedance Probability

1. Harbor Food Service Equipment	2. ADI Print Solutions	3. Biltrite	4. Greenroots
5. Eastern Minerals	6. Boston Hides & Furs	7. Carbone Metal Fabricator	8. Preflight Airport Parking BOS
9. WorldWide Perishables Inc	10. Enterprise Rent-A-Car	11. Chelsea employee parking lot	12. Interpark Preflight
13. Murray Supply			

Table 10: Businesses Affected in 2050- 21 inch Sea Level Rise and Flood with a 10% Exceedance Probability

1. Harbor Food Service Equipment	2. ADI Print Solutions	3. Biltrite	4. Greenroots
5. Eastern Minerals	6. Boston Hides & Furs	7. Carbone Metal Fabricator	8. Preflight Airport Parking BOS
14. WorldWide Perishables Inc	15. Enterprise Rent-A-Car	16. Chelsea employee parking lot	17. Interpark Preflight
18. Murray Supply	Designers Choice LLC	Enterprise Truck Rental	Mass Water Resource Authority
Paul Revere Transportation	Big T & D Air Freight Trucking		

4.4 Characterization of Transportation Network in Terms of Flooding Resilience

The 4R-5C method was used to determine the flood resiliency of the City of Chelsea by rating five categories, Human, Social, Physical, Natural, and Financial, and further breaking them down into the "4-R's", Robustness, Redundancy, Resourcefulness and Rapidity. We gave the City of Chelsea a B overall between all the categories. According to the grading criteria outlined in Figure 11, a grade of B means that the City of Chelsea has a "good chance with no immediate need for improvement" for recovering from floods; however, there is room for improvement. This section of the results chapter outlines a detailed breakdown of each individual category, with their independent grades and potential room for improvement. The criteria for each capital is outlined in the table of Appendix E. A specific analyzation of how each capital was graded is in Appendix F, Charts 1-5. We recognize that measuring resiliency is a complex issue and that when simplifying something as intricate as a city into five categories some important aspects of the city may be overlooked. All grades given in this report were determined by the group with the information available.

Table 11: Grading of 4R/5C Model

	Human	**Social**	**Physical**	**Natural**	**Financial**	**Overall**
Robustness	B	D	C	B	D	C
Redundancy	D	B	B	B	A	B
Resourcefulness	A	A	B	A	A	A
Rapidity	A	C	B	C	D	C
Overall	B	C	B	B	C	B

4.4.1 Results of the Human Capital Analysis

Overall, we allocated a B for the City of Chelsea on the grading scale for human capital in the 5C model; with a B in robustness, D in redundancy, A in resourcefulness, and an A in rapidity. The resourcefulness category measured the population health status by analyzing the disability rate for the under 65 age group and the percentage of people without health insurance. Chelsea was given an A because their average of 9.8% and 7.6% in each respective category is lower than the national average of 8.7% and 10.2%, when combined (U.S Census Bureau Quick Facts, 2018). Human rapidity was measured by flood vulnerability perception and management knowledge. A grade of A was given to Chelsea because the city has a plan for dealing with any form of natural disaster: the “Disaster Mitigation Plan.” This plan thoroughly details the risk that each form of natural disaster plays on Chelsea. Chelsea was given a B in robustness; that was measured by flood protective behavior and knowledge, the public involvement, and knowledge in protective measures. In the last category, redundancy, education was considered. The City has a high school graduation rate of 69.8% and 17.4% of residents have a bachelor’s degree compared to a national average of 87.3% and 30.9%, respectively (U.S Census Bureau Quick Facts, 2018). To receive a C the Chelsea average would need to be within 15% of the national average. These were averaged to deliver an overall grade of B.

4.4.2 Results of the Social Capital Analysis

The social capital measures the ability of the residents of the city to recover from a flood. Overall, we allocate the City of Chelsea a C on the grading scale for the social capital measured by the 5C model. For the four categories Chelsea we allocated a D in robustness, B in redundancy, A resourcefulness and a C in rapidity. Under resourcefulness the city has a HMP that outlines policies and plans for flooding risks along with many other risks the city could potentially endure. In the redundancy category, the city has an emergency alert system where residents can sign up for text or email alerts. The system can be easily accessed from the city website; however, it is not mandatory for all residents, meaning those who are not registered could potentially be unaware of pending emergencies or hazards. For rapidity, the strategy to maintain or quickly resume the local food supply in the event of a flood was picked by analyzing the impact on the New England Produce Center located in Chelsea. Part of the center is in the floodplain and would be partially inaccessible during a flood. The rest of the center will still be maintained but some of the trucking routes to distribute food around Chelsea will be impacted. The social vulnerability of Chelsea was evaluated for robustness using the Center for Disease Control and Prevention’s interactive online map. Since all of Chelsea lies within a high risk area with scores above 0.75 out of 1 for vulnerability, we allocated a D in robustness for this case. In summary, vulnerability is often seen as the opposite of resilience (SVI Interactive Map, 2016). For the City of Chelsea, the social vulnerability would have to decrease for the resilience of the network to improve.

4.4.3 Results of the Physical Capital Analysis

The physical infrastructure of a city is important in determining the resilience; the quality of city infrastructure can significantly impact the ability of a community to withstand a disaster. In the physical category, we allocated the City of Chelsea a C in robustness and B’s in redundancy, resourcefulness, and rapidity for an overall grade of B. The city’s utilities infrastructure were evaluated for robustness in terms of age and sufficiency. The water supply lines were built at the turn of the twentieth century, but were cleaned and cement lined in the 1970’s. The sewer lines were also built around the same time as a combined runoff and sewer system, but in the 1980's a separate drainage system was built in the Marginal Street area to mitigate overflows due to flooding and high amounts of runoff. These systems were designed for a peak demand at the time of construction; however, in recent years, capacity has been exceeded due to instances of more extreme flooding. On some occasions this has caused water and other contaminants to backflow through the catch basins and sewers into the streets, releasing contaminants into the Chelsea Creek. The Chelsea Creek was given an A- grade in the last water quality review by the Mystic River Water Association, in contrast to many other bodies of water in the area that received lower grades. Rapidity determines the rate at which issues can be fixed, which is an important aspect of the resilience of the city (MyRWA, 2017). The water and sewer systems do not have backup systems, which are uncommon in the municipal world. In the event of the overloading of these systems, the city must act quickly to fix the any resulting issues. In terms of redundancy, we looked at locations the City of Chelsea could use as a shelter in the event of an emergency. The city does have several locations that can be used as shelters in the event that a flood creates the need for people to be relocated from their homes. As such, we gave it a B because there are multiple locations for shelters and if there were more, the city could improve to an A. For resourcefulness, the city was given a grade of B the emergency alert system would be used to notify people of these emergencies but since signups for alerts are not mandatory, not everyone will know of the locations of these shelters. The physical resilience of Chelsea can be improved could increase the resilience.

4.4.4 Results of the Natural Capital Analysis

Another capital measured by the 5C model is the natural resources in the community. Here we allocated a B in robustness, B in redundancy, A in resourcefulness, and a C in rapidity. For robustness we looked at the health of the Chelsea Creek. In the 2017 MyRWA report for waterways in the Boston area, the Chelsea Creek received an A-. Under the redundancy category we looked at if the natural habitats maintained for their flood resilience. We gave it a B because of its grade with in the MyRWA report and the fact the city has a City Conservation Commission. For resourcefulness we looked at the city's plan for conservation management. Chelsea has a park space along Marginal Street and has plans for two more areas to be developed into park space next to the Chelsea Street Bridge. The City Conservation Commission released its Open Space and Recreational plan most recently in 2010 outlining its plans to conserve the natural resources of Chelsea and create more open spaces like parks. Overall the city is very prepared for conservation management and we allocated an A because of its efforts. Habitat connectivity was looked at in the rapidity category by looking at if the Chelsea Creek was flooded and the habitat was forced to relocate to the surrounding waterways. The three nearest waterways are Mill Creek, Island End River and the Mystic River. Mill Creek and the Island End River both received a grade of F while the Mystic River received a C (MyRWA, 2017). We allocated Chelsea a C in the rapidity category and it could be improved if those rivers improve and get healthier.

4.4.5 Results of the Financial Capital Analysis

Overall we gave the City of Chelsea a C on the grading scale for financial capital in the 5C model, including a D in robustness, A in redundancy, A in resourcefulness, and a D in rapidity. The area along Marginal Street has mandatory flood insurance guaranteeing that, in case of a damaging storm, businesses in the area would have the redundant capital to fix the damages. We allocated an A in resourcefulness because of a thorough disaster response plan detailing all potential disasters as laid out by FEMA, which outlines in detail any recent occurrences and the risk each event poses to Chelsea. Chelsea ranked lower in the robustness and rapidity categories. We allocated a D for Robustness due to an average household income of $51,839 in a state with an average household income of $74,167. Chelsea also has an average household income lower than the national average income of $57,652 (U.S Census Bureau Quick Facts, 2018). For the City to improve to a ranking of C in robustness, we felt it would need to improve average income to that of the national average. In rapidity, Chelsea’s poverty rate was graded. The poverty rate indicates an ability to cover unexpected expenses during the event of a flood. We allocated a D in rapidity due to a higher than average poverty rate. Chelsea has a poverty rate of 19.5% compared to a national average of 12.3% and a Massachusetts average of 10.5% (U.S Census Bureau Quick Facts, 2018). To improve to a rating of a C, we feel the City of Chelsea would have to reduce poverty to within 5% of the national average. Overall the city and its residents are moderately prepared to recover financially from a flood event, with the local businesses being better off than the town's residents.

4.5 Design Solutions

Due to Port Authority Restrictions and the location of Regulatory Floodways, any design wall will be located along the pedestrian walkway on Marginal Street. Using the map images generated for the 30 year flooding and sea level rise scenarios, we selected the optimal location in our focus area, with an approximate length of 0.35 miles, beginning at the Chelsea Street Bridge extending east to 240 Marginal Street. Figure 17, the 2050 flooding scenario, shows that past 240 Marginal Street, the floodwaters do encroach significantly on the shoreline or interfere with Marginal Street. As such, we decided that the structure could end at this point to reduce the overall magnitude of the structure, which reduces logistics issues like accessibility to businesses. The location is highlighted in Figure 21. There are clear disadvantages to this placement, such as the business and parking area which would be isolated on the water side of the wall. However, given sea level rise and flooding scenarios for the year 2050, this area through the park marked by the tree symbol are most vulnerable to flooding. For the exact limitations of flooding, refer to figure 17.

Figure 21. Proposed Location of Sea Wall from Chelsea Street Bridge to 240 Marginal St.

The soil at the area is comprised primarily of dark brown medium to fine sand, some silt, and some coarse to fine gravel, under three inches of asphalt and four inches of concrete. There is structural fill present at approximately five feet below grade to six feet below grade. The soil is primarily sand and silt to 15 feet below grade, where marine silt and clay are present.

The site is exposed to storm waters, flooding, and sea level rise from Chelsea Creek on the South/Southeast side. A review of the wave information from US Harbors resulted in an average wave height of 1.6 feet with a period of two seconds (US Harbors, 2018).

A critical component of any potential design is the placement of the element with respect to the shoreline and Chelsea Creek. In this case, the controlling factor was the Port Authority regulations for the focus area along Marginal Street. Figure 5 shows the boundaries of the designated port area; working with these regulations led us to an ideal location along the pedestrian walkway of Marginal Street. This placement is also justified by the recommendations by the USACE; their manual states that structures should be placed as far up the shore profile as possible to reduce risks from erosion. The structure design was chosen based on the restrictions of the selected location.

4.5.1 Comparison of Design Solutions

Design options for this project included bluffs, sheet pilings with bulkheads, concrete blocks, and mounds. Based on Table 13, the concrete block design is the most feasible in terms of size and cost. Mounds and bluffs would require the shoreline to be built up significantly; the shoreline along Marginal Street does not have the required space for these structures to be built to the appropriate magnitude. Research on similar sheet pile designs revealed that these structures are typically not cantilevered more than three feet above grade. In a case where a similar wall was cantilevered four feet above grade, the structure was driven more than 10 feet below grade (Naval Facilities Engineering Command, 2010). The required depth to cantilever the design more than eight feet above grade, as required in this case, is assumed to be proportionately greater, making this design less than feasible. The required depth of excavation along the edge of the street would undermine the structural integrity of the roadways, if installing for the 100 year flooding scenario in 2050. Installing a concrete sea wall in this location is more feasible, therefore, this design was selected for calculations.

Table 12: Types of Coastline Design Structures

Design Type	**Benefits**	**Disadvantages**
Low/High Bluff	Uneven surface and irregular gaps disperse waves through smaller channels, reduced total impact	Required design height calls for structure to be built further out on shoreline
Sheet Piling with Bulkhead	Good for areas less frequently battered by sea waters Groundwater can pass through drainage passages in the buried portion	Design typically relies on backfill/earth to provide support, not available along Marginal St Cantilevered design requires structure to be driven deeper than is reasonable
Concrete Block	Gravity structure can be built in selected location Lower Cost operations	Shorter lifespan Vertical design can be undercut by high wave energy
Mound	Natural type structure causes less disruption Slope allows for gradual dissipation of wave energy	Requires larger cross section than is ideal for location Shorter lifespan Cannot withstand high energy wave forces

After selecting a concrete block wall, we considered the type of solution that we would like to propose. For the most cost efficient and feasible option, we elected to present three potential options. The first of these is a design to accommodate flooding in 2030, which can be built upon and expanded into a design that could accommodate flooding in 2050, our second design solution. Finally, we investigated the use of a sheet pile wall to confirm or deny the feasibility of installation as a permanent solution for flooding in 2050.

4.5.2 Initial Design Case for 2030

The least imposing of our three design solutions was based on using the same blocks as were used to calculate the 2050 sea wall. In this case, one block plus a concrete cap is sufficient for the predicted ten year sea level rise. The calculations shown in Appendix L returned a design height of 3.5 for a design water level of 4.8 feet above sea level. MassDOT standard blocks of three and one half feet high by two and two thirds feet wide and four feet long were selected to achieve the design height. The concrete block and cap in this case should be tied together using rebar, drilled and grouted at each foot on center. Assuming a weight of 150 lbs. per cubic foot for concrete and a weight of 120 lbs. per linear foot for reinforcement, the structure weight was 1815.5 lbs. per linear foot of structure. These calculations were used for each of the two loading scenarios.

The bearing capacity of the soil came out to be 10,530.6 lbs. per linear foot for the structure based on a base width of 3.5 ft., using Prandtl's equation in Appendix L. Given the structure weight of 1815.5 lbs. per linear foot, the structure is not bearing down on the soil with enough for to cause shear failure in the soil.

4.5.3 Concrete Sea Wall Low Water Scenario for 2030

The elevation of the roadway at Marginal Street is assumed to be a uniform seven feet above sea level. In this case, no water would exert pressure on the sea wall. The calculations for the sea wall in a low water scenario, which are included in Appendix M, included the normal force, friction, and earth forces. The normal force was equivalent to the weight of the structure, 1815.5 lbs. per linear foot. Friction was 1270.8 lbs. per linear foot, calculated from an internal angle of friction of 35° and a coefficient of friction of 0.7. To calculate the force from the soil, the active earth coefficient, Ka, was calculated to be 0.3 with the Rankine Method. The earth forces were then equivalent to 160.4 lbs. per linear foot.

The forces acting on the wall were then used to calculate the sliding and overturning stability of the structure. Sliding stability is calculated by dividing the stabilizing force, friction, by the anti-stabilizing force, the earth force, to achieve a factor of safety of 7.9 against sliding. Therefore, when designed to meet these requirements, the structure will not slide. The overturning stability about the heel of the structure was calculated by dividing the moments from the structure weight by the moments from the earth forces. The factor of safety against overturning was 39.6. Therefore, the structure will not overturn in this loading condition.

4.5.4 Concrete Sea Wall Design Water Level and Wave Height Scenario for 2030

The calculations for when the structure is under the maximum loading scenario, the maximum sea level rise and flooding combined are in Appendix N. These calculations rely on the wave forces, hydrostatic forces, earth forces, friction, the weight and the normal force. First, the coefficients for the Goda formula were modified to fit our structure design. With these, we calculated P1 to be 176.7 lbs. per square foot, P2 to be 0 lbs. per square foot and P3 to be 176.5 lbs. per square foot. PU for wave uplift was 136.6 lbs. per square foot. These were used to calculate the final wave pressures, using the levels of uncertainty for each value. The sum of the horizontal wave forces was 303.8 lbs. per linear foot and the wave uplift force was 526.1 lbs. per linear foot.

Given the wave and buoyant uplift force, the resultant normal force was calculated as the difference between the weight and the wave uplift. This provides a value of 1289.4 lbs. per linear foot. The friction value was calculated using the normal force and a coefficient of friction of 0.7 to be 902.6 lbs. per linear foot.

The earth forces were calculated using a passive earth pressure coefficient, Kp, which was calculated to be 3.7 using the Rankine Method. The earth force was then determined to be 2192.3 lbs. per linear foot. The hydrostatic forces were calculated at 3.2 lbs. per linear foot.

All of these values are then used to determine the overturning and sliding stabilities. For sliding stability, the stabilizing forces were the sum of the friction and earth forces and the anti-stabilizing forces were the sum of the total uplift and hydrostatic forces. Dividing the stabilizing forces by the anti-stabilizing forces gives a factor of safety of 10.1. Therefore, the structure is not a risk of sliding in this loading scenario. The overturning stability was calculated by dividing the stabilizing moments by the anti-stabilizing moments. The stabilizing moments are the sum of the weight and the earth forces multiplied by their respective moment arms about the structure heel.

The total value is 14277.4 foot-lbs. per linear foot. The anti-stabilizing moments are the sum of the hydrostatic, wave uplift, and horizontal wave forces multiplied by their respective moment arms. The total value is 4291.5 foot-lbs. per linear foot. Performing the calculation provided a factor of safety of 3.3. Therefore, the structure is not at risk of overturning in this scenario.

4.5.5 Initial Design Case for 2050

The USACE manual recommends that concrete seawalls consisting of precast blocks are stacked a maximum of three high and two wide. The calculations shown in Appendix G returned a design height of eight feet. MassDOT standard blocks of three and one half feet high by two and two thirds feet wide and 4 feet long were selected to achieve the design height. A second row of concrete blocks was added to increase the weight and reduce risk of sliding or overturning. The concrete blocks should be tied together using rebar, drilled and grouted at each foot on center. Assuming a weight of 150 lbs. per cubic foot for concrete and a weight of 120 lbs. per linear foot for reinforcement, the structure weight was 9,307.5 lbs. per linear foot of structure. These calculations were used for each of the two loading scenarios.

The bearing capacity of the soil came out to be 21,061.2 lbs. per linear foot for the structure based on a base width of 7 ft., using Prandtl's equation in Appendix H. Given the structure weight of 9307.5 lbs. per linear foot, the structure is not bearing down on the soil with enough for to cause shear failure in the soil.

4.5.6 Concrete Sea Wall Low Water Scenario for 2050

In cases of low water, the mean tide elevation in Chelsea Creek will be 3.8 ft. in 2050 (FEMA, 2017). The elevation of the roadway at Marginal Street is assumed to be a uniform seven feet above sea level. In this case, no water would exert pressure on the sea wall. The calculations for the sea wall in a low water scenario in Appendix H, included the normal force, friction, and earth forces. The normal force was equivalent to the weight of the structure, 9,307.5 lbs. per linear foot. Friction was 6115.2 lbs. per linear foot, calculated from an internal angle of friction of 35° and a coefficient of friction of 0.7. To calculate the force from the soil, the active earth coefficient, Ka, was calculated to be 0.3 with the Rankine Method. The earth forces were then equivalent to 991.2 lbs. per linear foot.

The forces acting on the wall were then used to calculate the sliding and overturning stability of the structure. Sliding stability is calculating by dividing the stabilizing force, friction, by the anti-stabilizing force, the earth force, to achieve a factor of safety of 6.6 against sliding.

Therefore, the structure will not slide. The overturning stability about the heel of the structure was calculated by dividing the moments from the structure weight by the moments from the earth forces. The factor of safety against overturning was 21.9. Therefore, the structure will not overturn in this loading condition.

4.5.7 Concrete Sea Wall Design Water Level and Wave Height Scenario for 2050

The calculations for when the structure is under the maximum loading scenario, the maximum sea level rise and flooding combined are in Appendix I. These calculations rely on the wave forces, hydrostatic forces, earth forces, friction, the weight and the normal force. These forces acting upon the design structure are shown in the force diagram in Figure 22.

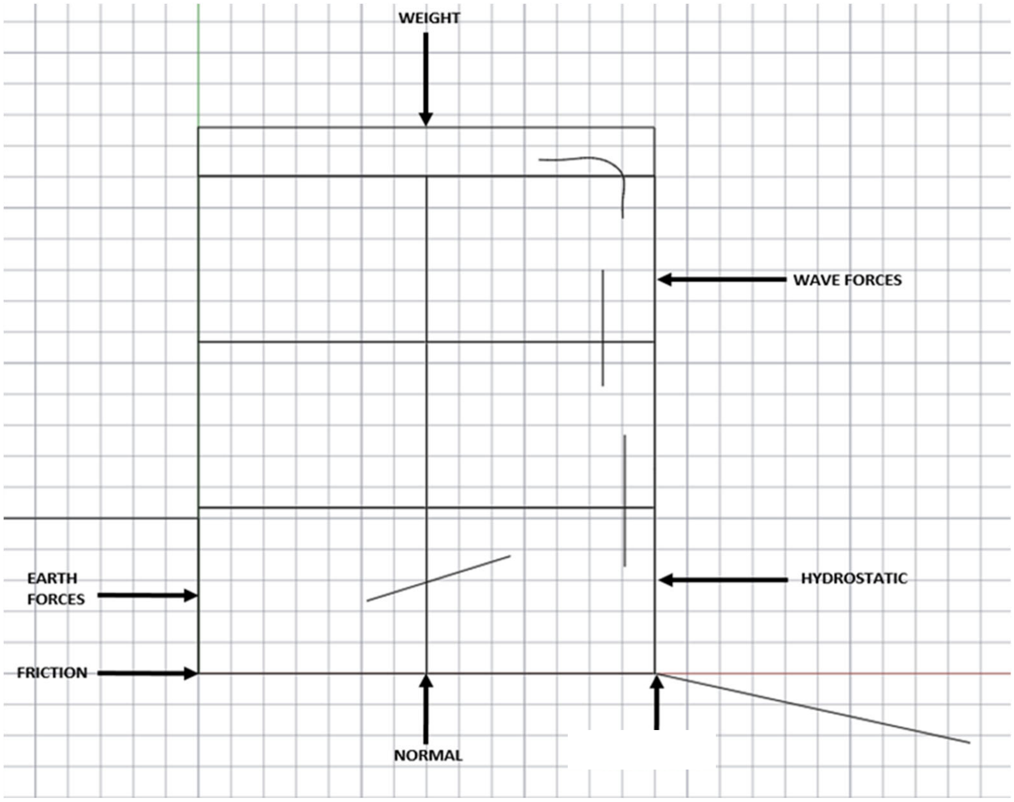


Figure 22. Force Diagram for Water Design Level Scenario

First, the coefficients for the Goda formula were modified to fit our structure design. With these, we calculated P1 to be 91.4 lbs. per square foot, P2 to be 18.3 lbs. per square foot and P3 to be 56. 4 lbs. per square foot. PU for wave uplift was 56.4 lbs. per square foot. These were used to calculate the final wave pressures, using the levels of uncertainty for each value. The sum of the horizontal wave forces was 537.6 lbs. per linear foot and the wave uplift force was 217 lbs. per linear foot. The loading scenario for the specific wave pressures is shown in Figure 23.

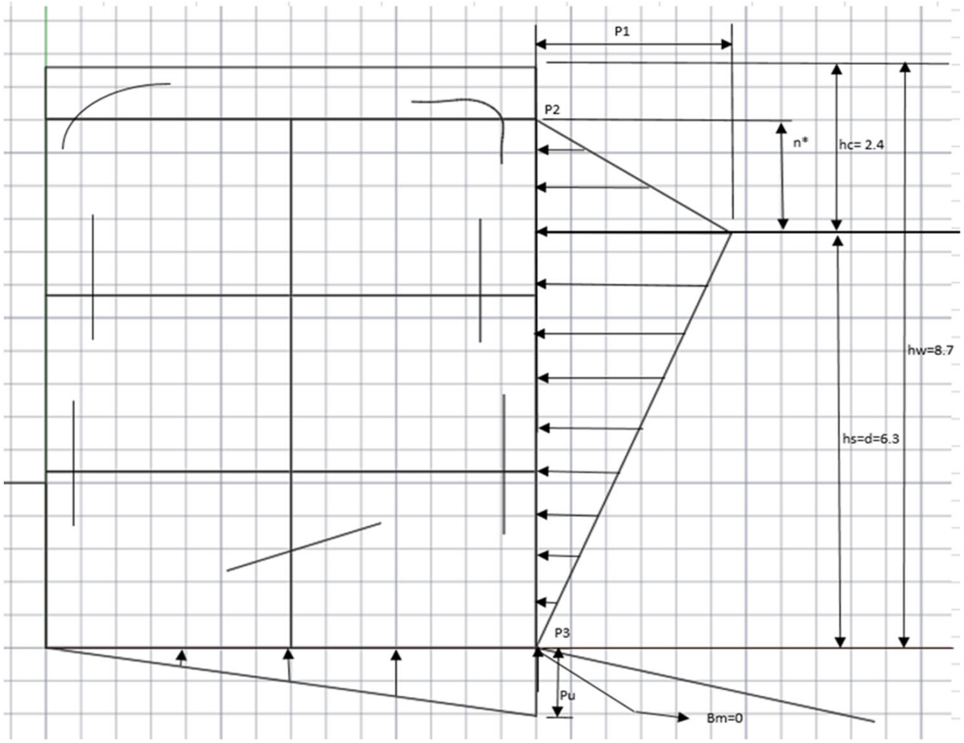


Figure 23. Force Diagram of Wave and Hydrostatic Pressures on the Design Cross Section

Given the wave uplift force, the resultant normal force was calculated as the difference between the weight and the wave uplift. This provides a value of 9090.5 lbs. per linear foot. The friction value was calculated using the normal force and a coefficient of friction of 0.7 to be 6363.4 lbs. per linear foot.

The earth forces were calculated using a passive earth pressure coefficient, Kp, which was calculated to be 3.7 using the Rankine Method. The earth force was then determined to be 13,545.9 lbs. per linear foot. The hydrostatic forces were calculated at 1238.3 lbs. per linear foot.

All of these values are then used to determine the overturning and sliding stabilities. For sliding stability, the stabilizing forces were the sum of the friction and earth forces and the anti-stabilizing forces were the sum of the wave uplift and hydrostatic forces. Dividing the stabilizing forces by the anti-stabilizing forces gives a factor of safety of 11.2. Therefore, the structure is not a risk of sliding in this loading scenario. The overturning stability was calculated by dividing the stabilizing moments by the anti-stabilizing moments. The stabilizing moments are the sum of the weight and the earth forces multiplied by their respective moment arms about the structure heel.

The total value is 57,548.8 foot-lbs. per linear foot. The anti-stabilizing moments are the sum of the hydrostatic, wave uplift, and horizontal wave forces multiplied by their respective moment arms. The total value is 5,068.7 foot-lbs. per linear foot. Performing the calculation provided a factor of safety of 11.4. Therefore, the structure is not at risk of overturning in this scenario.

4.5.8 Software Loading in Risa 3D Results

Our calculations were input into Risa a total of three times to verify the viability of the structure. This was done by modeling a cross section of one foot and modeling the loading per linear foot on this. The model of the cross section can be viewed in Figure 24.

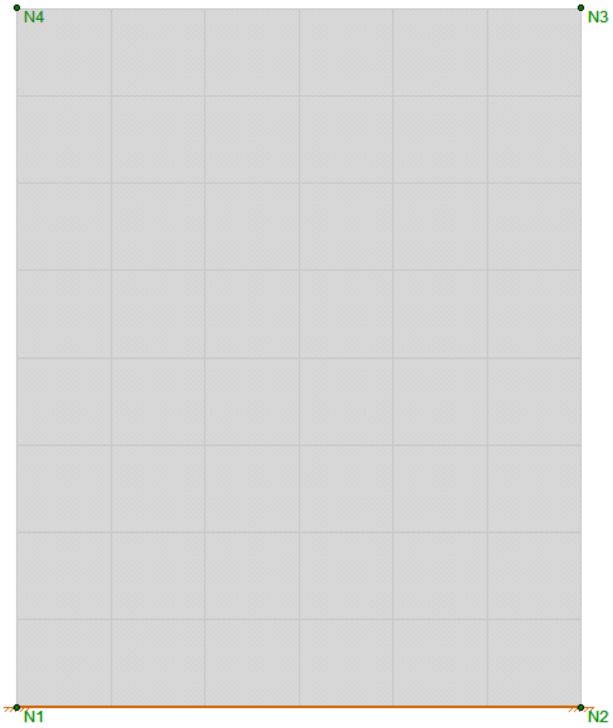


Figure 24. Risa 3D Front View of Cross Sectional Model

Each of the three attempts returned the same results in Appendix J. The loading interaction diagram can be seen in Figure 25. The in plane interaction diagram shows the sliding and overturning forces and moments in a simultaneous scenario. The values are equivalent within a 5% margin of error to the manual calculations. Risa returned a maximum axial or bending value of 0.005, which does not significantly impact our design. Therefore, the initial calculations are valid and the structure is sound.

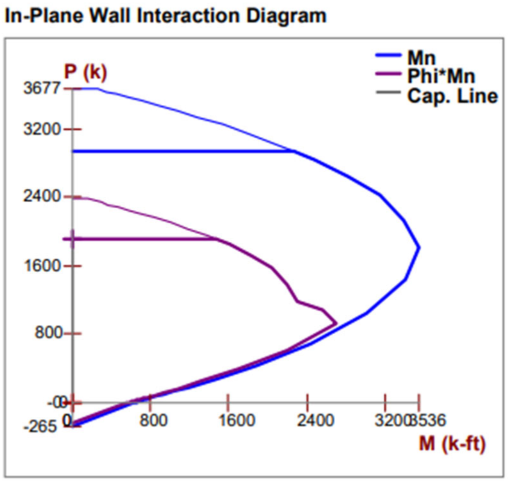


Figure 25. Risa 3DIn-Plane Wall Interaction Diagram

4.5.9 Software Model

The design structure was modeled in AutoCAD. Figure 25 represents a cross sectional layout view of the design.

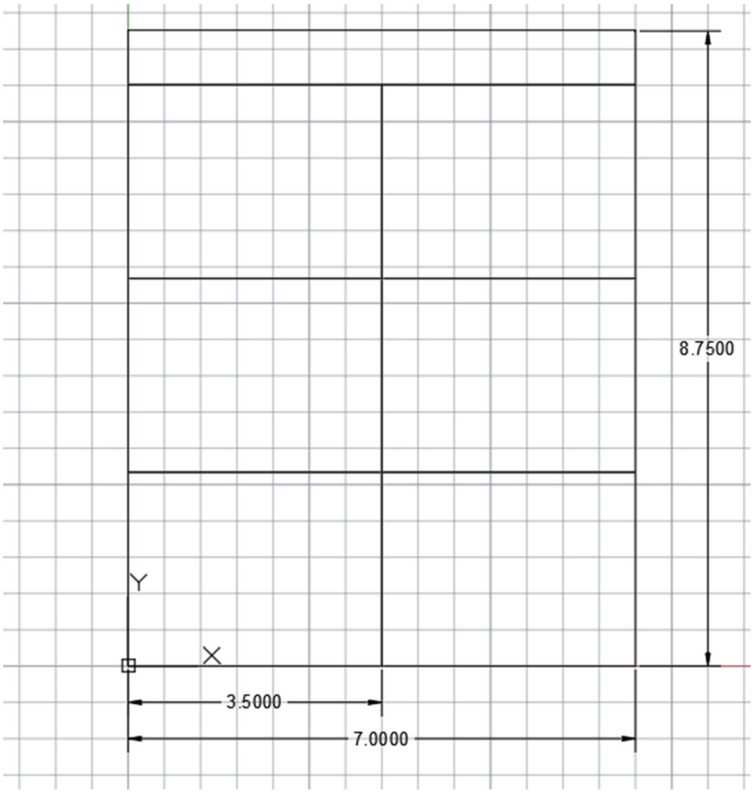


Figure 25. Section View of 3D Model

Figure 26 shows the 3D model extruded along the 0.35 mile location highlighted in Figure 20.

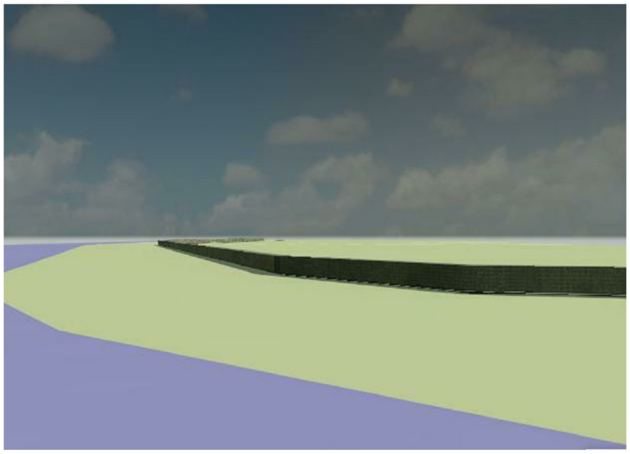


Figure 26. Model of Sea Wall Extruded along Selected Design Location

This displays the magnitude of the structure in the proposed location along Marginal Street.

4.5.10 Sheet Pile Wall

Our investigation into the use of the sheet pile wall design returned several issues which lead us to exclude these results from our report. To begin, sheet pile walls are more typically used to hold back land or water in a temporary matter and are not typically designed for long term use. Designing a cantilevered sheet pile for long term use requires in depth soil analysis to ensure the design would not fail; we do not currently have access to the required soil information to evaluate this option. As such, it would be unreasonable to suggest this as a long term solution for the City of Chelsea. We could have possibly used this solution for a wall if we could have built it along the waterfront but because of the chapter 91 regulations that was not feasible. If we did put a sheet pile wall along the roadway it would just be sheet piles sticking up out of the ground; the base of the wall and ground elevation would be the same on both sides, and the sheet metal would need to extend approximately 9 feet above grade. The ASCE does not provide design standards or regulations for a wall of this nature.

Typically cantilevered, sheet pile walls are used to hold back land or water in a situation where land has been excavated, and there is a difference in the dredge elevation and normal grade. The metal is shaped to prevent deflection and the wall is additionally anchored into the soil behind it and the sheet does not extend above normal grade more than a few inches. If we were to recommend driving this pile, we would need to consider the deformation of the wall under the weight of water pressing against it in flooding scenarios, for which no regulating agency or organization provides standards. Additionally, this design would likely require the installation of reinforcement, like steel framing, to prevent the sheet from bending, which could negate the benefits of a slimmer design compared to the concrete wall. Overall, we feel that we would not be able to design a sheet pile wall to an adequate standard to ensure safety and sustainability.

4.5.11 2030 Concrete Sea Wall Cost Estimate

Estimating the cost of the smaller concrete wall design was a function of the material cost and the labor cost. This number does not account for overhead, indirect, or other potential costs, such as overtime police. The concrete was costed by cubic yard. For a total of 840 CY, the supply cost breaks down to 90$ for materials and $65 for trucking, amounting to $130,200 dollars. For labor, we estimated that the crews would be able to complete 25 foot section in three days. We carried a mason, and three laborers for a total of 21 days. At Massachusetts prevailing wages, the total labor cost was $152,185 dollars. This brings the total cost to $282,396 dollars. Assuming the variability of the actual cost to be -50% to 100%, the actual cost could range between $141,198 dollars and $562,792 dollars. Given the sparse nature of components in our estimate, we predict that the higher variability would be more accurate.

4.5.12 2050 Concrete Sea Wall Cost Estimate

Estimating the cost of the larger concrete wall design for 2050 was also a function of the material cost and the labor cost. This number does not account for overhead, indirect, or other potential costs, such as overtime police. For a total of 4,200 CY, the supply cost breaks down to 90$ for materials and $65 for trucking, amounting to $651,000 dollars. For labor, we estimated that the crews would be able to complete 25 foot section in three days. We carried a mason, and three laborers for a total of 75 days. At Massachusetts prevailing wages, the total labor cost was $592,763 dollars. This brings the total cost to $1,243,763 dollars. Assuming the variability of the actual cost to be -50% to 100%, the actual cost could range between $621,881 dollars and $2,487,526 dollars. Given the sparse nature of components in our estimate, we predict that the higher variability would be more accurate.

4.5.13 Effects of Concrete Sea Wall Installation

The installation of a concrete sea wall will affect any normal processes which require movement between the pedestrian walkway and the shoreline. This includes drainage from higher elevations that is draining towards the creek and businesses that may be inaccessible if the wall is built. Currently, any drainage directed towards the wall site identified in Figure 20 will potentially cause ponding or water collection. In the event the city decides to implement this solution or similar, they would also need to consider design plans to the current drainage system to avoid this issue. In addition, the design solution we suggest would trap a business on other side of the wall, rendering it inaccessible. Our placement was meant to limit the number of businesses trapped; however any structure placed to optimally combat flooding will inevitably require businesses to relocate.

5.0 Conclusions and Recommendations

After a review of the City of Chelsea’s network resiliency to flooding, we were able to recommend several solutions to combat flooding. Chelsea is vulnerable to flooding as soon as 2030 in high tide and severe storm events, and this vulnerability will continue to increase as climate change leads to more severe and frequent storms and increasing sea levels. The results of these floods can be costly and lengthy repairs to recover the use of roads and businesses in impacted areas. To look at specific areas of vulnerability and resiliency, we first mapped the extent of flooding given certain criteria, such as predicted sea level rise and storm surge due to climate change. This enabled us to evaluate the extent to which the Marginal Street area would be impacted by flooding, providing a basis for a quantitative analysis of resilience to flooding. We used this information to develop several recommendations for the City of Chelsea to follow in order to increase resiliency and preparedness in a flooding event. One of these recommendations, a sea wall design, was fully explored over the course of several months, resulting in one concrete block design which can be built up over time to combat sea level rise and flooding from the Chelsea Creek.

From the results of our report, we created several recommendations for the city of Chelsea to best enhance their resilience to flooding. Our recommendations for the City of Chelsea are as follows:

- Establish alternate traffic routes to accommodate through traffic along Marginal Street in the event of flooding. There should special attention paid to maintaining truck routes for food distribution from the New England Produce Center. These routes should be clearly marked by street signage and published in an emergency management plan.
- Increase awareness efforts to increase public knowledge of emergency response measures, including evacuation routes, emergency alert systems, and shelter locations.
- Investigate replacing and redesigning the current drainage system to reduce flooding from runoff and increase capacity.
- Increase the number of public facilities that are equipped to become emergency shelters in the event of flooding.
- Implement a sea wall design solution along Marginal Street to prevent flooding that would impact traffic along the roadway.

- Consider solutions to relocate businesses located in vulnerable flood zones on the Chelsea Creek side of Marginal Street.

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Appendix A: Project Proposal

Assessing and Reducing the Impacts of Flooding on Transportation in the City of Chelsea, Massachusetts

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January 19th, 2019

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1. Introduction

Planet Earth has experienced cyclical climates change for millennia; however, the most recent warming trend is unique in that scientists from NOAA, the IPCC, and other research organizations have shown that this trend is the result of human activity (IPCC, 2018). Since the 1800's the average temperature of the Earth has increased by 1.92 degrees Fahrenheit, as humans continually release greenhouse gases into the atmosphere. Using ice cores drawn from glaciers from around the globe the National Research Council proved that the Earth's climate varies in response to these greenhouse gases (NRC, 2017). As carbon dioxide emissions continue to increase, the planet has seen the five hottest years on record in the past decade alone (NRC, 2017). The effects of a warming Earth on various climates around the planet stem from this upward trend in global temperature.

More specifically, the IPCC highlights the acceleration of sea level rise beginning in the 1900's as a result of climate change (IPCC, 2018). Decades later, analysis of research and samples by the International Drilling Program and the U.S. National Science Foundation estimates that a sustained period of two degree Fahrenheit temperature rise could lead to between 20 and 30 feet of sea level rise (Wilson, et al., 2018). According to the Penn State Earth System Science Center, as many as 650 million people around the globe live on land that is threatened to be chronically or permanently flooded due to sea level rise (Maines, 2018). The East Coast of North America, in the Atlantic and Gulf Area, is expected to see a steep increase in coastal and tidal flooding due to low flooding thresholds and a sinking coastline. Many East Coast communities are now seeing dozens of tidal floods each year. Some communities have seen a fourfold increase in the annual number of days with tidal flooding since 1970. In the next 15 years, two-thirds of these communities could see a tripling or more in the number of high-tide floods each year. (Spanger-Siegfried, 2014).

The City of Chelsea, Massachusetts, covering approximately two squares miles northeast of Boston, is one these vulnerable East Coast Communities as sea levels rise and floods increase in frequency. Projections from 100 year flood maps provided to the city by FEMA show key transportation routes and industrial areas are particularly vulnerable to flooding and storms. These maps clearly represent the vulnerability of the Marginal Street area, which serves as a major transportation area; thru truck traffic along this route and surrounding routes is three to five times higher than similar regional areas, and other traffic is expected to increase over 13%

with the addition of a casino to the Boston area (Stantec, 2018). The City Planning Department is aware of the looming threats to Chelsea's infrastructure, and is actively seeking solutions to increase the resiliency of the local transportation network along the Marginal Street corridor, Figure 1.1.

Figure 1.1. Map highlighting the area of Marginal Street in Chelsea where the project is focused.

This Major Qualifying Project will involve working with the City of Chelsea as our sponsors to develop recommendations and actionable plans to prepare the Marginal Street area for increased flooding and storm events. We plan to analyze the effects of increased flooding on the transportation network, including the effects of diverting traffic from flood areas and the effects of flooding on all aspects of infrastructure. To do so, we will look at defined parameters for flooding, using predictions for 50 and 100 year storms, and predicted increments of sea level rise over the next 100 years. We will use the results of these analyses to highlight the importance of both preventing and mitigating damage from flooding, both to traffic networks and flooding infrastructure. This will include design elements meant to combat flooding events from flood or storm water, such as a sea wall and a traffic plan. A set of several recommendations based on our findings will be provided to the City of Chelsea to aid in their efforts to improve their resilience to climate change.

2. Background

Climate change refers to a range of global trends primarily resulting from the release of greenhouse gases in the Earth's atmosphere (IPCC, 2018). Experts predict that climate change will lead to a variety of negative consequences, among them increased frequency of severe weather patterns and accelerated sea level rise (CCSP, 2008). These events are raising concern in coastal communities, like the City of Chelsea, as they recognize a need to prepare for the impending realities of climate change.

2.1 Impact of Climate Change

Effects of climate change include rising temperature trends, precipitation patterns, storm surges, sea level rise, and decreasing ice mass (EPA 2016). The global temperature increase accelerated global sea level rise resulting in approximately eight inches of rise above 1880 levels. This temperature increase will continue to accelerate sea level rise. A Climate Central analysis found the frequency of damaging flooding would increase throughout the U.S. as a result, primarily in coastal cities and communities (Strauss, Tebaldi & Zlemlinksi, 2012).

2.1.1 Potential Impacts in the Northeast United States.

Climate change will impact coastal areas in a variety of ways. Coasts are vulnerable to seal level rise, changes in frequency and severity of storms, warmer ocean temperatures, and increasing precipitation (EPA, 2016). Due to the effects of climate change, coastal cities will be faced with challenges of recovery and resilience of their environment: including ecosystems, shoreline erosion, coastal flooding, and water pollution, and infrastructure (EPA, 2016). The degradation of these elements will have an impact on coastal city functions and their ability to effectively withstand storms in the future.

Eastern seaboard cities are projected to experience these effects acutely. Figure 2.1 illustrates the Eastern seaboard has historically experienced greater increases in sea level compared to other coastal areas in the U.S. For instance, New York City is expected to see two to nine inches of sea level rise with 90% confidence by 2030. Atlantic City will see a four to eleven inch rise, Bridgeport, CT and Newport, RI will each see two to nine inch rises. By 2050 sea level rise is expected to more than double in major cities compared to 2030 (Strauss, et al., 2012). In Boston Harbor, the 90% confidence interval for sea level rise is two to nine inches with a “best estimate” of five inches by 2030, and twelve inches by 2050 (Strauss, et al., 2012).

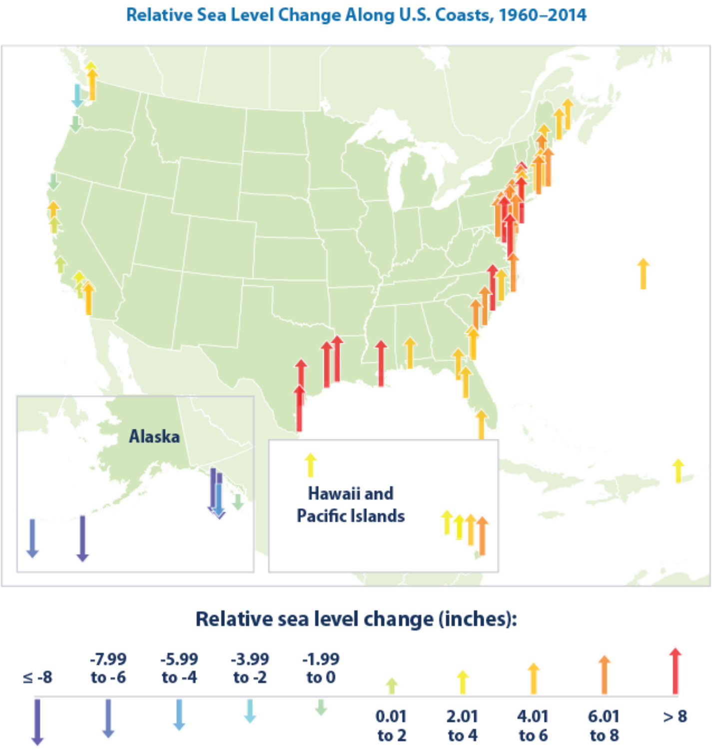


Figure 2.1. The map demonstrates relative sea level rise and retreat along U.S. coastlines with a series of color coded arrows (NOAA, 2017).

2.2 Impact of Climate Change on the City of Chelsea

The City of Chelsea is similarly vulnerable to sea level rise and increased flooding. Rates of relative sea level rise from 2000 to 2050 in the Boston area according to the Boston Research Advisory Group, will be between 7.5, 13 and 18 inches “with exceedance probabilities of 83%, 50%, and 17%,” respectively. (BRAG, 2016, pp.6). Extreme models indicate a possible 30 inch sea level rise by 2050, after which sea levels will continue to rise (BRAG, 2016). Estimates for sea level rise in the year 2100 show water levels at a projected maximum of seven and one half feet from 1880 levels. Projected sea level rise will eventually drown saltwater marshes and become tidal flats and sub-tidal bays (BRAG, 2016). These transition habitats serve as a buffer zone between the ocean and land. Saltwater marshes are able to ease the effects of low grade storms but flooding from climate change will greatly hinder these ecosystem’s abilities (New Hampshire Department of Environmental Services, 2004). In addition, rising sea levels increase wave energy, tidal range, and inundations resulting in further erosion of the coastline (BRAG, 2016). Higher sea levels are correlated with an increase in coastal flooding, and evidence suggests that a rise of more than one foot will trigger hazardous flooding in affected regions (BRAG, 2016). Marginal Street is located along the Chelsea Creek and is one of the most vulnerable areas within the city.

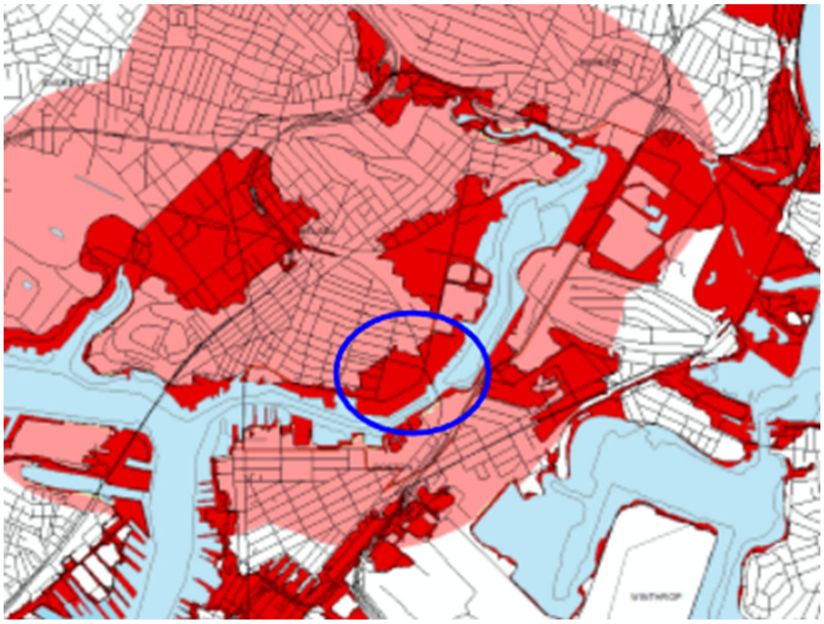


Figure 2.2. Map illustrating flood projections from FEMA with Marginal Street inside the blue outline. The red shaded areas represent predicted sea rise after a hundred year flood event and the pink shaded areas represent predicted sea level rise after a five hundred year flood event.

Around 50% of Chelsea is in a designated flood plain, placing the city at risk; local sea-level rise will directly impact infrastructure of that area through increased flooding events. The USGS is describing substantial flooding events as, “a flood having a 100-year recurrence interval” (USGS, 2018, pp.1). One hundred year floods, despite what the name implies, actually have a one in one hundred chance of occurring each year. Figure 2.2 illustrates that the mid latitudes, as of 2010, experience such weather events at over 200% of the frequency in the 1970s, and at 75% higher intensity. These storms are expected to include both 50 and 100 year flooding events. Coastal cities need to prepare for changes in sea levels and storm activity. As such, the City of Chelsea plans to adjust their resiliency strategy to account for these increased weather events, partly by using the findings of this Major Qualifying Project.

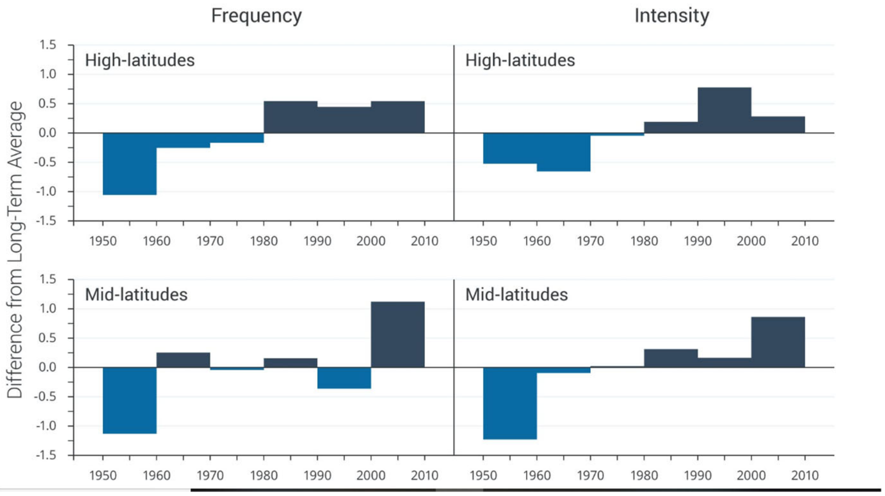


Figure 2.3 Bar graphs which represent the increased frequency and intensity of weather events over the past 60 years over two latitudinal areas.

2.3 Vulnerabilities of Flooding and Severe Storms

Flooding can have a multitude of impacts on its environment including sheet erosion, infrastructure damage, and ecosystem destruction. In the event of flooding, sheet erosion is likely to occur. Sheet erosion can degrade soils and roadways causing landslides, mudslides, and deterioration of paved and unpaved roadways. Structures, such as buildings or bridges, face worse potential damage from long standing floods rather than temporary floods. In either case, damage to road infrastructure will directly affect transportation and accessibility within Chelsea. Many forms of transportation are affected by flooding like road, rail, and air travel. Some airports, like Boston's Logan International Airport, which is built right on the coast and at sea level, could be susceptible to submerged runways, although aviation overall is generally the least affected (Titus, 2002). Railroads, especially in cities near the coast, are vulnerable to flooding because tracks are frequently placed in low or marsh-like areas which could sink or washout from under the tracks (Titus, 2002). Tunnels used by subway systems and roadways as they pass below sea level are vulnerable to flood waters that overcome the flood walls blocking the water from rushing down the tunnel. For example, in New York City recent major storms have completely flooded tunnels in lower Manhattan. One other risk with flooding above tunnels is the increase in water causes a correlating increase in the hydraulic pressure on the tunnel. Roads are the most vulnerable transportation system to flooding because water causes them to be impassable. Road closure can prevent emergency crews from reaching areas in need and people from evacuating in a timely fashion; therefore, endangering their safety (Titus, 2002).

2.3.1 Flooding and Stormwater Impact on City of Chelsea's Infrastructure

The occurrence of flooding damage to structures is dependent on several factors, including "the depth of water in and around the structure, the length of time of inundation, the toxic extent of contaminants in floodwaters, and how rapidly the water is moving" (FEMA, 2011, pp. 18). A flow of water moving at 10 mph exerts the same amount of pressure on a structure as wind gusts of 270 mph and can cause sudden destruction of buildings and roadways. Water that sits in structures for extended periods of time can damage the integrity of the structure, "particularly the wood foundation pilings, structural beams, carpets, wood floors, cabinetry, mechanical systems, utilities, and walls." (FEMA, 2011, pp. 18). Chelsea has previously experienced flooding along various roadways, including Marginal Street and is expected to experience increased flooding instances as sea levels rise. For that reason, evaluating the current and potential damage caused by flooding is an important aspect of this project.

2.3.2 Flooding and Stormwater Impact on Chelsea's Traffic and Transportation Networks

Climate change will impact transportation system networks to varying degrees. The integrity and conditions of road infrastructure impacts traffic flow, and sea level rise increases vulnerability of transportation services, and influences the reliability of modes of transport. Flooding and inundation of segments of transportation systems can disrupt connectivity of regions and accessibility within the city (CCSP, 2008). As a result, traffic delays are expected with road closures and detours, straining the transportation systems. These transportation systems are integral to Chelsea's industrial economy and provide important functions to Boston. Marginal Street contains a salt pile utilized by regions in the area during the winter season, and functions as an evacuation route for Boston (Stantec, 2018). Industrial and commercial buildings are located in the Marginal Street area such as the Boston Logan International Airport parking services that serves hundreds of airport employees and customers. Flooding or failure of infrastructure on Marginal Street will interrupt local traffic, regional accessibility, and the safety of transportation networks.

2.4 Case Studies and Preventative Measures

Recovering from floods is a long and costly endeavor. Longevity of flooding impacts the severity of damage; floods that rise and recede quickly cause less damage than floods when water sits for weeks. Large storms and major hurricanes regularly cause billions of dollars in damages. The most significant recent storms were Hurricane Katrina and Hurricane Harvey. In August of 2005 Hurricane Katrina hit the East Coast, displacing more than a million people and causing 161 billion dollars in damage. Twelve years later, in August of 2017 Hurricane Harvey destroyed 204 thousand homes while causing 125 billion dollars in damage (NCEI, 2018).

The damage from hurricanes and other large storms are not only costly but can also displace residents from their homes and can take years to recover to previous infrastructure conditions. Flooding can destroy homes, uproot communities, while causing massive amounts of damage. Consequently, the post flood clean up and recovery process requires planning and funding. Preventative measure should be taken when applicable. Many of the solutions to combat flooding are adaptations to existing infrastructure. Ideas such as seawalls, early notifications systems, drainage and retention systems, levees, dikes, and dams are effective methods of reducing the impact of flooding. Communities implementing adaptation methods will find themselves better equipped for floods and combined with preventative methods will significantly reduce infrastructure damage, and environmental and economic impacts.

2.4.1 Sea Walls

Sea walls can be an effective method of reducing the impact of storm surges; however, they do not come without complications. Seawalls are susceptible to failure from overtopping, and often provide a false sense of security for communities. Specifically, “seawalls smaller than five meters in height appear to have encouraged development in vulnerable areas and exacerbated damage.”(Nateghi, 2016, pp. 4) However, Nateghi, an author with the Public Library of Science, points out that “seawalls larger than five meters in height generally have served a protective role in past events, reducing both death rates and the damage rates of residential buildings” (Nateghi, 2016, pp. 4). From this source, it is clear that height is a determining factor in the structural soundness of seawalls. If this is a chosen method of remediation then other factors such as material composition and width of the wall will also need to be researched for consideration.

2.4.2 Drainage/Retention Systems

Urbanization has created the need for new drainage systems, referred to as stormwater management systems. These systems seek to maximize convenience to individual sites by rapidly removing excess surface water after rainfall through a closed conveyance system

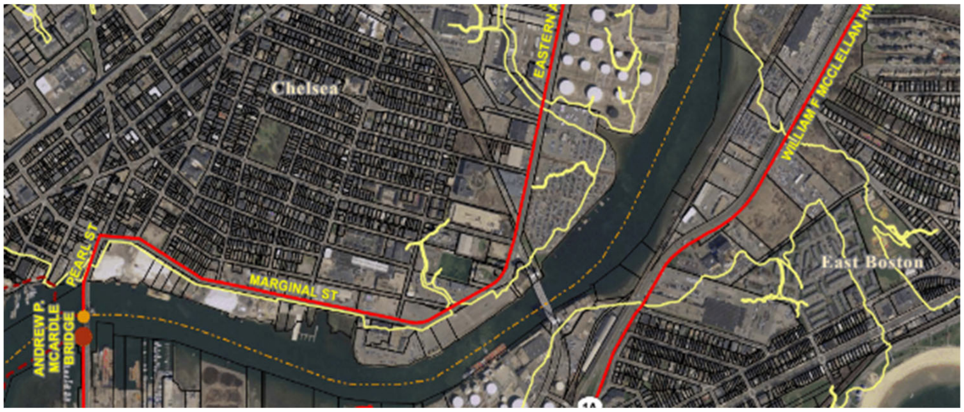
(FEMA, 2011). While current stormwater management systems do an adequate job managing the storms of today, with rising sea levels and increasing intensity of storms, such systems will be inadequately equipped to handle storm surges in the near future. However, FEMA, in regards to drainage systems, notes that "the cumulative effects of such an approach has been a major cause of increased frequency of downstream flooding, often accomplished by diminishing groundwater supplies, as direct results of urbanization" (FEMA, 2011). For this reason, this report will not suggest the use of a stormwater retention system alone to combat flooding in the City of Chelsea.

2.5 Limitations

The area of interest in this project borders waterways which are regulated by the state. Chapter 91 of the Massachusetts State Legislature: Waterways Act was passed in order to control the use of designated port areas, such as the area of interest along Marginal St. This act set regulations for all of the waterways in the state. It encompasses everything from the duties of local departments of public works and landowners, permitting and zoning, and rules on removal of tidelands.

2.5.1 Designated Port Area

The City of Chelsea has part of its coast line designated as a port area which brings special regulations to what the land on the water can be used for. The satellite image in Figure 2.3 shows the areas of Chelsea that are designated as a port area between the water and the red line. The area between Marginal Street and the water is in the designated port area meaning that the regulations in the area will need to be considered when proposing solutions for the city.



F*igure 2.4. The image shows the Designated Port Area in the City of Chelsea with the red perimeter line (MASSACHUSETTS OFFICE OF COASTAL ZONE MANAGEMENT).*

3. Objectives and Methodology

To meet our overarching goal of evaluating and improving the transportation resiliency of the Marginal Street area, we have created a series of objectives to guide our project. Figure 3.1 demonstrates the logical flow of our project.

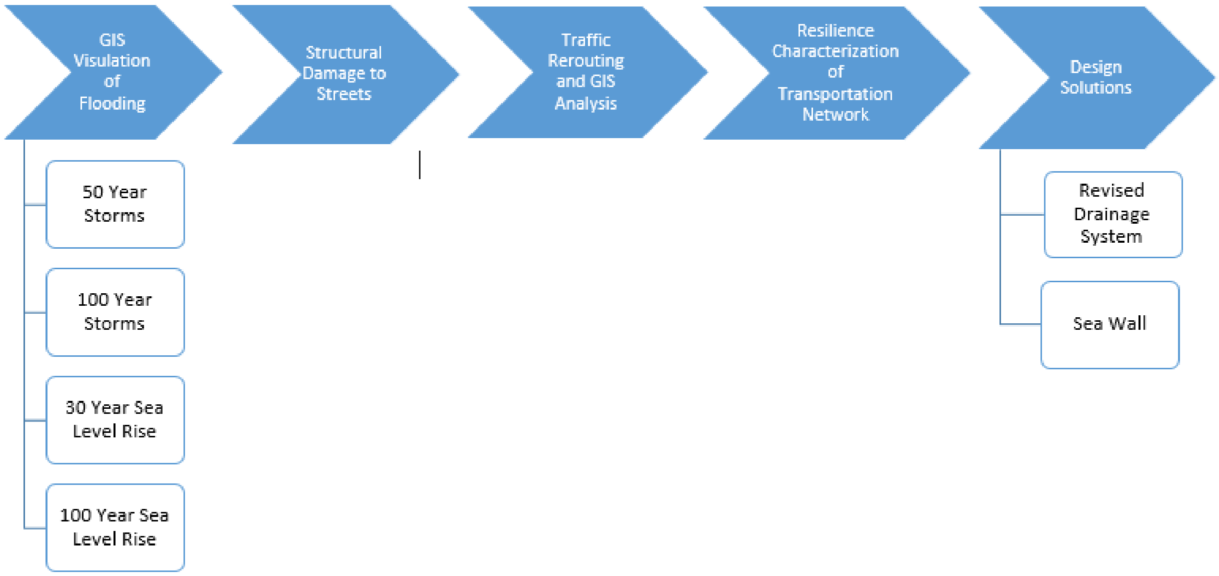


Figure 3.1. The objectives of the project represented in logical order with hierarchical detail.

We will use the four control scenarios shown in Figure 3.1 to evaluate flooding, and for each of these scenarios will evaluate the impact on the traffic network, flooding and transportation infrastructure, and cost of recovery. We have more thoroughly stated these objectives as follows:

- Evaluate flood damages to roads and transportation infrastructure in Chelsea due to varying floodwater scenarios.
- Assess extent of the impact flooding will have on vehicle and pedestrian transportation and identify alternative routes.
- Assess the potential environmental and economic impact incoming floodwaters or sea level rise will have on the Marginal Street corridor.
- Create a design such as a sea wall to combat rising sea levels and increased instances of flooding

In order to reach these objectives, we have outlined a methodology that will allow us to effectively complete our tasks. We will complete these tasks according to the schedule in Appendix A.

3.1 Evaluate Flooding Under Potential Scenarios

Recommending a course of action to increase the transportation resiliency of local roadways begins by understanding previous research and products. We conducted a preliminary phase of research into current climate trends and projections, transportation infrastructure, and traffic flow of the local area. We decided to focus our research on temporary instances of 50 and 100 year flooding events, as well as prolonged flooding from the minimum and maximum sea level rise, as predicted by NASA.

3.2.1 Compiling GIS Data

Geographic Information Systems (GIS) is a comprehensive method to view large quantities of data. As additional information is collected throughout the project, the data is converted into data map layers. Updated traffic data from the Massachusetts Department of Transportation will be made into a map to view how the city is strained in terms of transportation. Currently, we do not have access to separate data maps for flooding strictly due to sea level rise or due to precipitation rain events, therefore we will address flooding instances congruently. Utilizing available data we will create GIS map layers for the flooding events. These layers will be used for reference and further analyzed to determine potential impacts on the area of interest. Maps generated will include flooding extent and range due to sea level rise and future precipitation patterns. Maps of a 50 year and 100 year predictions will be created based on estimated climate data.

3.3 Analyzing Traffic Impacts

To complete our project we will analyze data found to offer solutions. We have identified the necessary information integral to this project, and have received existing data provided by the city’s planning department and the Massachusetts Department of Transportation. This includes traffic volume data for Marginal Street and extrapolated data to quantify the vulnerability of the roadway to damage from flooding.

3.3.1 Traffic Networking

Utilizing traffic data provided by Massachusetts Department of Transportation we will develop an understanding of traffic flow within Marginal Street and its surrounding area. For streets with such high traffic, a hand count or use of a counter box would allow for an accurate measure of traffic flow, but would be extremely time inefficient. We will rely on published traffic data from the Massachusetts Department of Transportation and ESRI. We will look at increments of severe flooding and determine which routes will be impassable and what routes could be available to detour motorists. We will calculate the increased traffic flow and make informed predictions as to how this will slow traffic. The roads that will be on the evacuation routes will need to handle an increase in traffic for timely evacuation.

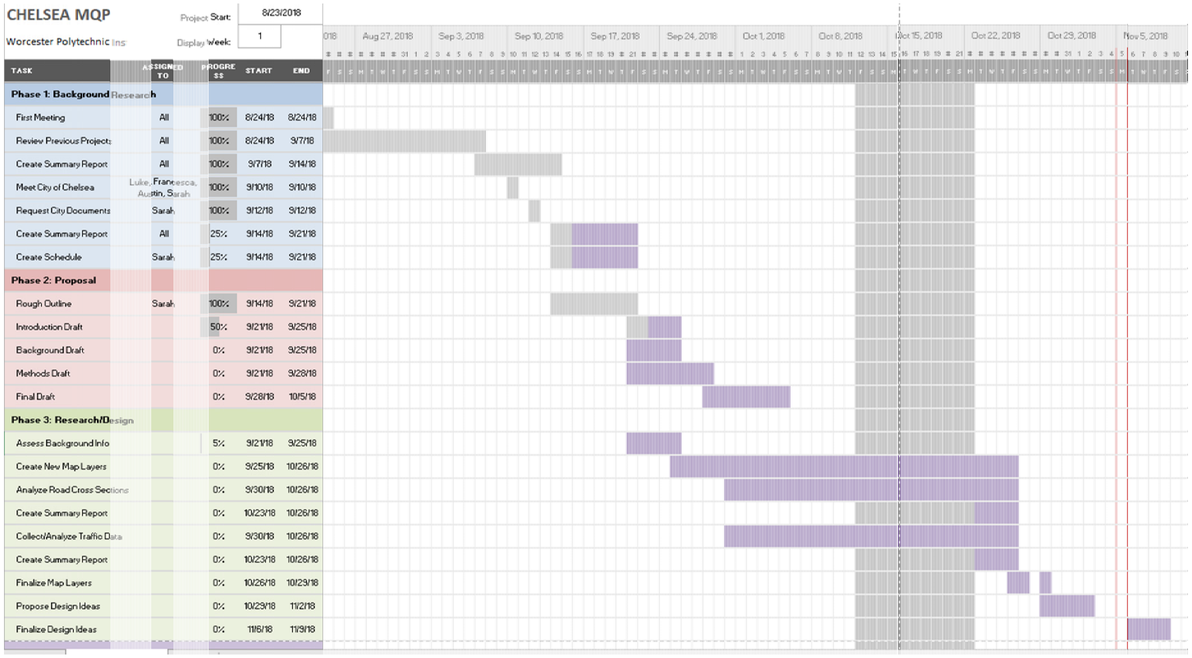
3.3.2 Damage to Roadways

Flooding can cause varying types of damage to roadways, depending on the material used to pave the road and the density and permeability of the existing surface. Although, no method of analysis is as accurate as pulling actual samples of the layers of asphalt and grade, this method is not feasible for project. Using standard as built conditions for Marginal Street, we can ascertain the material, mix, and thickness of the asphalt surface. We will use academic tools developed to predict the vulnerability of roadways to flood induced damage. We can therefore predict the likeliness of the surface to crack or warp due to loss of stiffness/stability, and likeliness to erode.

3.4 Design

When designing solutions to combat the impacts of global warming a range of solutions has to be considered. There will be no “one size fits all” solution but rather a combination of multiple design elements suited to Marginal Streets exact specifications to deliver the most efficient result. Given the nature of future sea level rise and flooding events, a sea wall is the most logical solution. First, we will consider the location of the design, and determine what length of Marginal Street is appropriate and whether the wall should possibly continue beyond the scope of our work. Then, we will use allowable stress design to engineer a seawall to the appropriate dimensions and thickness for the project. We will confirm these calculations using software RISA 2D and rely on the input of accomplished engineers in the field. Then we will model our final design using SolidWorks.

Appendix B: Gantt Chart



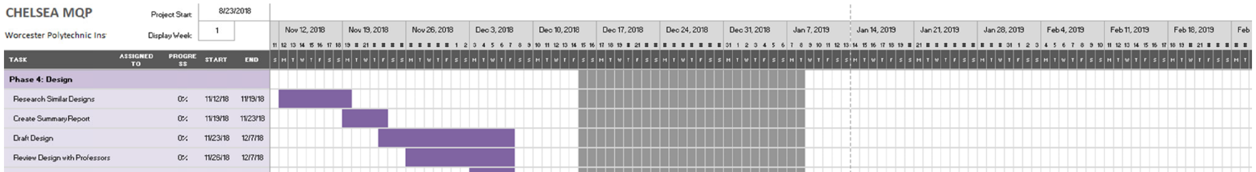
CHELSEA MQP

Worcester Polytechnic Ins

Project Start: 8/23/2018

Display Week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
Phase 1: Background Research				
First Meeting	All	100%	8/24/18	8/24/18
Review Previous Project:	All	100%	8/24/18	9/7/18
Create Summary Report	All	100%	9/7/18	9/14/18
Meet City of Chelsea	Luke, Francesca, Austin, Sarah	100%	9/10/18	9/10/18
Request City Documents	Sarah	100%	9/12/18	9/12/18
Create Summary Report	All	25%	9/14/18	9/21/18
Create Schedule	Sarah	25%	9/14/18	9/21/18
Phase 2: Proposal				
Rough Outline	Sarah	100%	9/14/18	9/21/18
Introduction Draft		50%	9/21/18	9/25/18
Background Draft		0%	9/21/18	9/25/18
Methods Draft		0%	9/21/18	9/28/18
Final Draft		0%	9/28/18	10/5/18
Phase 3: Research/Design				
Assess Background Info		5%	9/21/18	9/25/18
Create New Map Layers		0%	9/25/18	10/26/18
Analyze Road Cross Sections		0%	9/30/18	10/26/18
Create Summary Report		0%	10/23/18	10/26/18
Collect/Analyze Traffic Data		0%	9/30/18	10/26/18
Create Summary Report		0%	10/23/18	10/26/18
Finalize Map Layers		0%	10/26/18	10/29/18
Propose Design Ideas		0%	10/29/18	11/2/18
Finalize Design Ideas		0%	11/6/18	11/9/18



CHELSEA MQP

Worcester Polytechnic Ins

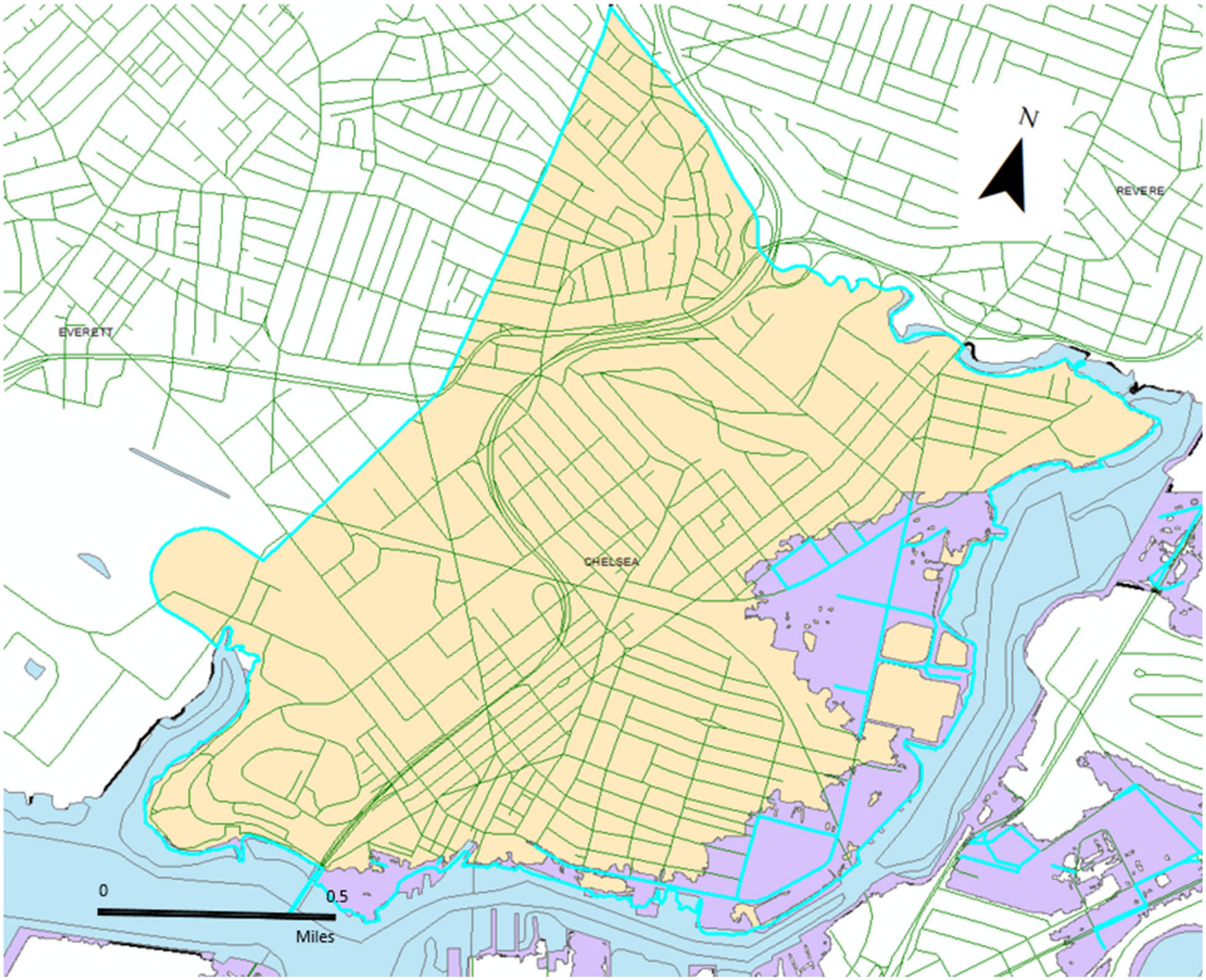
Project Start: 8/23/2018

Display Week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
Phase 4: Design				
Research Similar Designs		0%	11/12/18	11/19/18
Create Summary Report		0%	11/19/18	11/23/18
Draft Design		0%	11/23/18	12/7/18
Review Design with Professors		0%	11/26/18	12/7/18

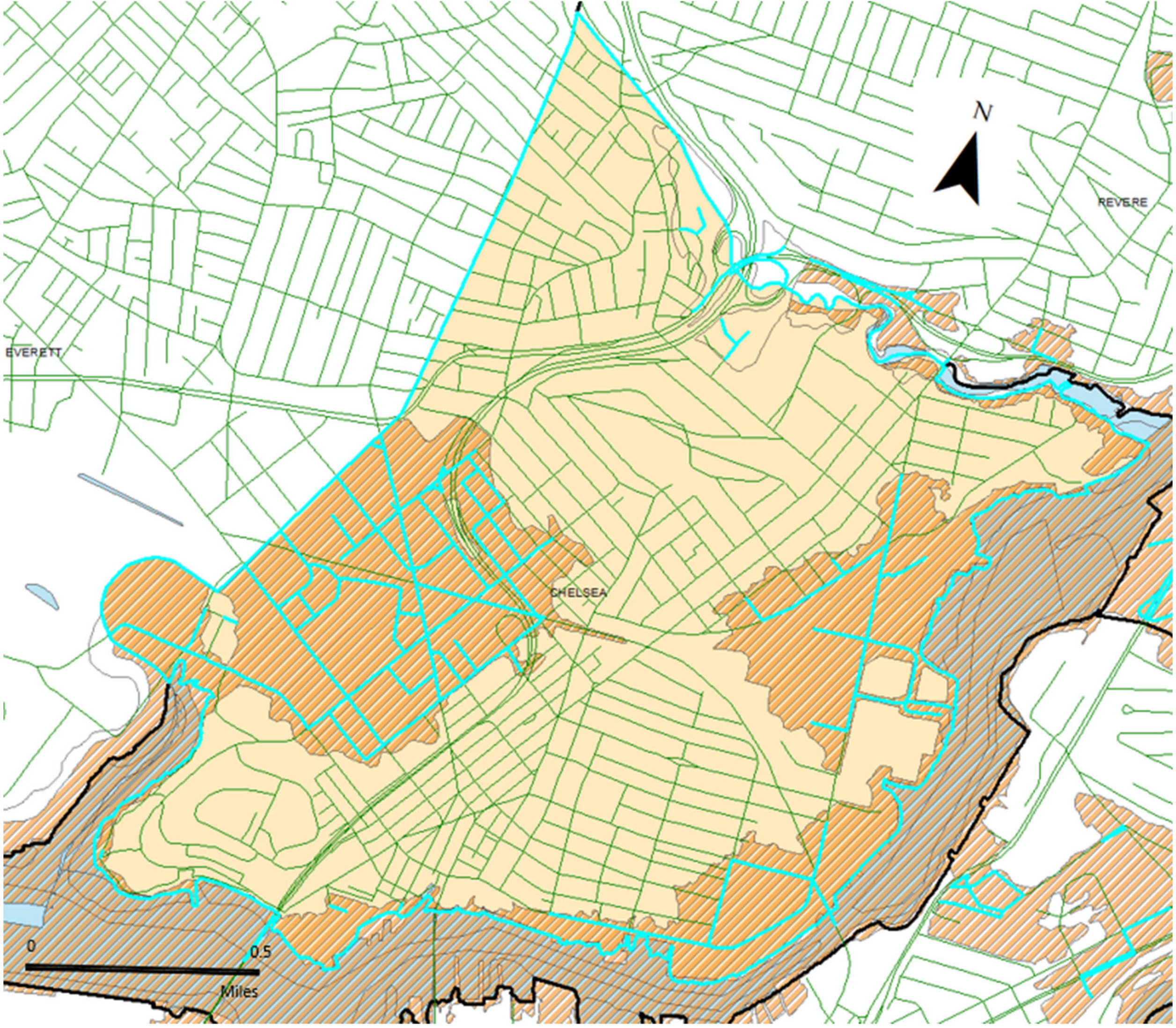
Appendix C: Flooding Scenarios

Flood Scenario #1



Map X: Chelsea is highlighted in yellow. The purple gradient is the 2050 year flood layer. The Cyan highlighted streets are within the affected flood area.

Flooding Scenario #2



Map X: Chelsea is highlighted in yellow. The orange gradient is the FEMA 1% flood layer. The Cyan highlighted streets are within FEMA flood layer.

Appendix D: Flooding Designation Explanation Table

Zone	**Description**	**Present in Chelsea**	**Depiction**
AE: 1% Annual Chance of Flooding with BFE	The base floodplain where base flood elevations are provided	Yes	Orange lined gradient fill
A: 1% Annual Chance of Flooding, no BFE	Areas with a 1% annual chance of flooding and a 26% chance of flooding over the life of a 30-year mortgage	Yes	Yellow and gray striped gradient fill
AE: Regulatory Floodway	The base floodplain where base flood elevations are provided	Yes	Light blue dotted gradient fill
AH: 1% Annual Chance of 1-3ft Ponding, with BFE	Areas with 1% annual chance of shallow flooding, usually in the form of a pond, with an average depth ranging from 1 to 3 feet. These areas have a 26% chance of flooding over the life of a 30-year mortgage. Base flood elevations derived from detailed analyses are shown at selected intervals within these zones.	No	Not present in Chelsea
AO: 1% Annual Chance of 1-3ft Sheet Flow Flooding	Rivers or stream flooding hazard areas, and areas with 1% or greater chance of	No	Not present in Chelsea

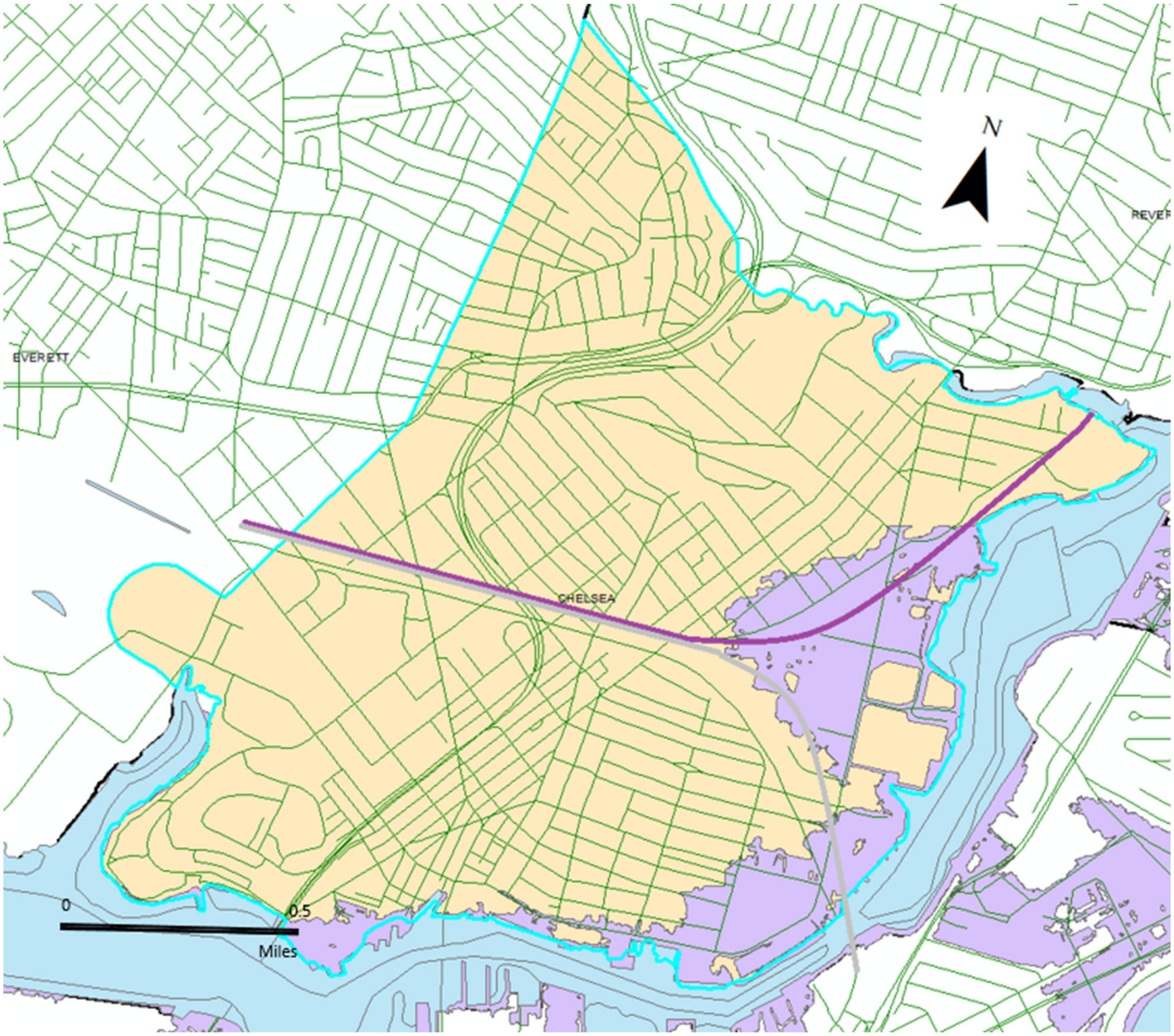
	shallow flooding each year, usually in the form of sheet flow, with an average depth ranging from 1 to 3 feet. These areas have a 26% chance of flooding over the life of a 30-year mortgage, Average flood depths derived from detailed analyses are shown within these zones.		
X: 0.2% Annual Chance of Flooding	Area of minimal flood hazard, described as a five hundred year flooding scenario.	Yes	Blue green gradient fill

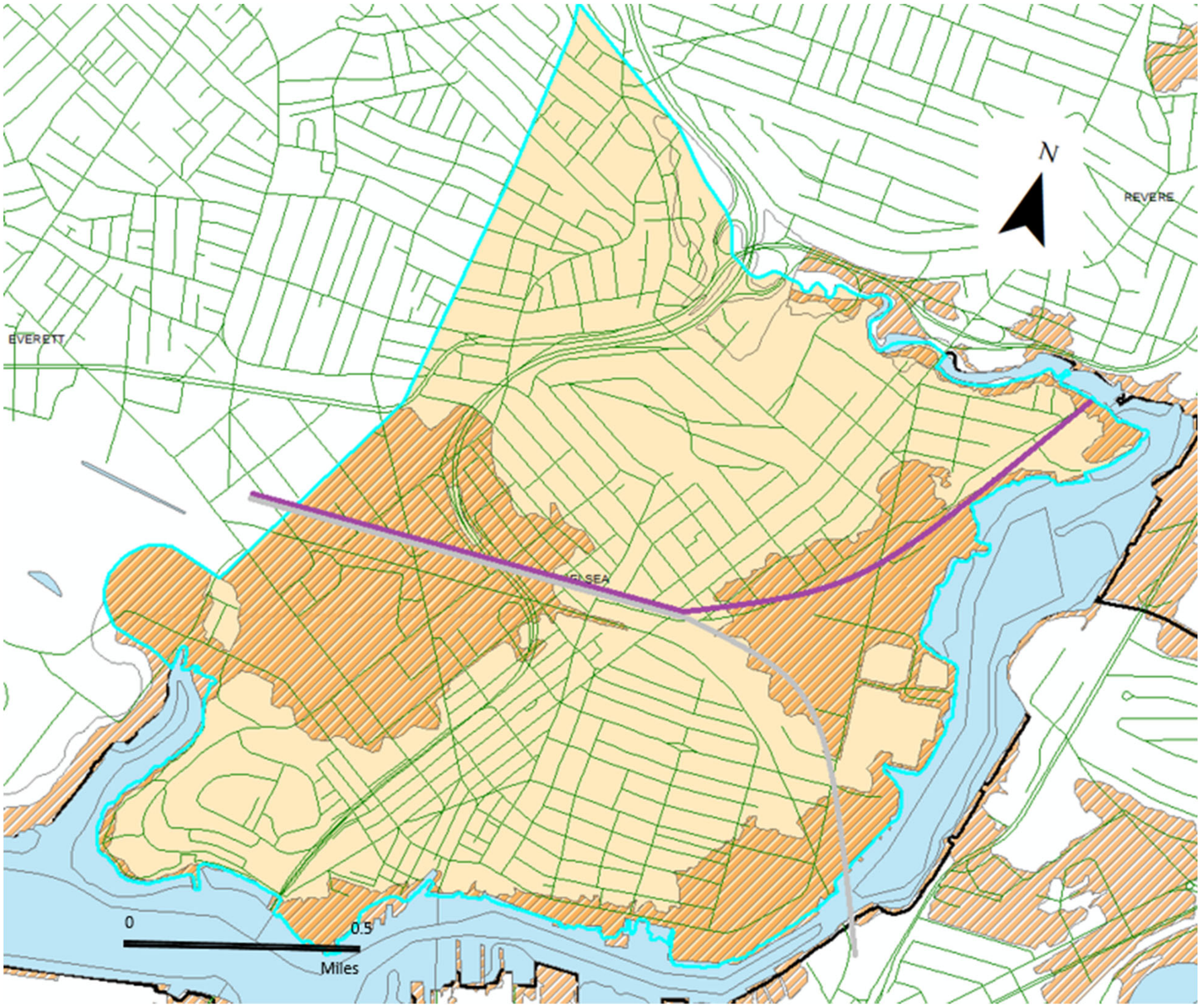
Appendix E: Flooding Affecting Railways in Chelsea

Flooding Scenario #1

Purple-commuter rail

Silver-silver line




N
REVERE
EVERETT
ELSEA
0
0.5
Miles

Appendix F: 4R/5C Overview

	Human	**Social**	**Physical**	**Natural**	**Financial**
Robustness	Flood protective behavior and knowledge	Social Vulnerability	Age of necessary infrastructure	Basin health	Income and affordability
Redundancy	Education	Functionality of communication networks	Access to school and healthcare facilities	Natural habitats maintained for their flood resilience services	Flood insurance
Resourcefulness	Population health status	Government policies and planning and mainstreaming of flood risk	Early Warning Systems (EWS)	Conservation management plan	Disaster response plan
Rapidity	Flood vulnerability perception and management knowledge	Strategy to maintain or quickly resume provision of local food supplies in the event of a flood	Food security, water supply and access to materials for building	Habitat connectivity	Poverty

Appendix G: 4R/5C Analysis

Chart 1: Human

	Human	**Analyzation**	**Grading Criteria**	**Risk Grade**
Robustness	Flood protective behavior and knowledge	The City of Chelsea has a hazard mitigation plan that outlines commonly flooded areas. It also outlines the future risk from climate change Population of Chelsea Public meetings held but from documentation no comments on plan except requests for special permits. https://www.chelseama.gov/sites/chelseama/files/uploads/cityreviewchelsea_draft_plan_update_5-16-14.pdf Appendix C	A - City has a plan to deal with hazardous situation with significant public involvement and activism. B - City has a plan to deal with hazardous situation with some public involvement. C - City has a plan to deal with hazardous situations. D - No information is available from the City.	B
Redundancy	Education	High School graduate or higher: 69.8% Bachelor's degree or higher: 17.4% Boston: 86.1%, 47.4% respectfully United States: 87.3%, 30.9% respectfully Source: https://www.census.gov/quickfacts/fact/table/US,bostoncitymassachusetts,chelseacitymassachusetts/INC910217	A - Graduation rate is above national average B - Graduation rate is with 5% of national average C - Graduation rate is within 15% of national average D - Graduation rate is more than 15% lower than national average	D

Resourcefulness	Population health status	People under 65 with Disability: 9.8% People without health insurance under 65: 7.6% Boston: 8.7, 4.2% respectfully United States: 8.7%, 10.2%	A - Health insurance and disability rate combined below national average B - Health insurance and disability rate combined at or below national average C - Health insurance and disability rate combined within 2.5% of national average D - Health insurance and disability combined more >2.5% of national average	A
Rapidity	Flood vulnerability perception and management knowledge	Management - very good detailed plans of all vulnerabilities now and in the future - Very realistic	A - City has a thorough plan for dealing with any form of natural disaster B - City has a detailed plan of how to deal with many natural disasters C - City has a rough plan of how to deal with various natural disasters D - City has no plan available for dealing with natural disasters	A

Chart 2: Social

	Social	**Analyzation**	**Grading Criteria**	**Risk Grade**
Robustness	Social Vulnerability	Social Vulnerability is graded on a scale of 0-1 with 1 being most vulnerable Chelsea has a 0.862 Source: https://svi.cdc.gov/map.html	A - 0-0.25 B - 0.25-0.5 C - 0.5-0.75 D - 0.75-1	D
Redundancy	Functionality of communication networks	Emergency Alert system, Verizon Transfer station not in Fema Floodplain, City has access to a mobile command unit (HMP)	A - City mandates all citizens sign up for emergency alert and have backup communication network plans B - Alert system in place but not mandated to citizens C - Limited alert system D - No plan for backup communication network plans or alert system	B
Resourcefulness	Government policies and planning and mainstreaming of flood risk	Hazard Mitigation Plan outlines planning for flood risks	A - City has a HMP outlining planning for all risks including those from floods B - City has a HMP outlining planning for flood risks C - City has a small or scarce HMP outlining planning for flood risks D - City has no HMP	A
Rapidity	Strategy to maintain or quickly	Kaymen Food Grocery store not in Fema floodplain- from hazard mitigation plan New England Produce Center-Food	A - City has a plan for providing food in the event of a flood with redundancies.	C

	resume provision of local food supplies in the event of a flood	Distribution Center, part in floodplain, distribution by railroad and trucks not really affected	B - City has a plan for providing food in the event of a flood and the distribution center is not in the flood plan C - City has a plan for providing food in the event of a flood but the distribution center is prone to flooding D - City has no plan or no available information on food distribution during flood	

Chart 3: Physical

	Physical	Analyzation	Grading Criteria	Risk Grade
Robustness	Age of necessary infrastructure	Water supply and sewers along Marginal St upgraded in the 1970's and 80's, built in the 1900's, Separate drainage lines built in the 1980's, flooding hasn't damaged lines but has caused backups and released CSO's into Chelsea Creek before	A - Necessary infrastructure was built or updated in the last 10 years B - Necessary infrastructure was built or updated in the last 25 years C - Necessary infrastructure was built or updated in the last 50 years D - Necessary infrastructure was built over 50 years ago.	C
Redundancy	Access to school and healthcare facilities	To be used as shelters and healthcare facilities: Mass General Healthcare Facility (Everett Ave) Schools: Chelsea High School (Everett Ave) George F Kelly Elementary (Crescent Ave) Phoenix Academy (Hawthorne St) Clark Avenue School (Clark Ave) Joseph A Browne School (Walnut St) St Rose School (Broadway) Seaport Academy (Commandants Way) Mary C Burke Elementary (Crescent Ave)	A - City has a significant number of public known safety locations that are at or above flood levels. B - City has several publicly known safety locations that are at or above flood levels. C - City has several publicly known safety locations during natural disasters D - City does not make the public aware of safety location during natural disasters	B
Resourcefulness	Early Warning Systems	Yes, Emergency Alert System, sign up on city website, text and email alerts (Reverse 911 system)	A - City mandates all citizens sign up for emergency alerts B - Alert system in place but not	B

	(EWS)		mandated to citizens C - Limited alert system D - No alert system	
Rapidity	Food security, water supply and access to materials for building	Water (MyRWA)- from Quabbin reservoir, pumping station not in Fema floodplain Food and materials No backup water supply system, deal with problems on an as needed basis. Designed for peak demand but that has been exceeded before Chelsea Creek received an A-	A - City has access to excess water supply and food supply to feed both their own population and surrounding areas B - City has enough access to water supply and food supply to feed the population during a natural disaster C - City has access to water supply and food supply during natural disaster D - City has no plan for feeding and getting water to the public during natural disasters	B

Chart 4: Natural

	Natural	Analyzation	Grading Criteria	Risk Grade
Robustness	Basin health	Chelsea creek received an A- rating from MyRWA in 2017 https://mysticriver.org/news/2017/6/30/mystic-river-receives-a-water-quality-grade	A - Meets 90%+ of MA water quality standards for swimming and boating. B - Meets 80%+ of MA water quality standards for swimming and boating. C - Meets 70%+ of MA water quality standards for swimming and boating. D - Meets <70% of MA water quality standards for swimming and boating.	B
Redundancy	Natural habitats maintained for their flood resilience services	Chelsea creek received an A- rating from MyRWA in 2017 City Conservation Commission	A - Meets 90%+ of MA water quality standards for swimming and boating. B - Meets 80%+ of MA water quality standards for swimming and boating. C - Meets 70%+ of MA water quality standards for swimming and boating. D - Meets <70% of MA water quality standards for swimming and boating.	B
Resourcefulness	Conservation management plan	Open Space and Recreation plan, city conservation commission overlooks natural resources (John DePreist is the head)	A - City has a city conservation commission and a conservation management plan B - City has a city conservation commission or a conservation management plan C - City has a rough conservation	A

			management plan D -City has no conservation management plan	
Rapidity	Habitat connectivity	Grading of surrounding areas from the MyRWA Report Chelsea Creek A- Mill Creek- F Island End River- F Mystic River- B	A - Surrounding areas have an average of an A B - Surrounding areas have an average of an B C - Surrounding areas have an average of an C D -Surrounding areas have an average of an D	C

Chart 5: Financial

	Financial	**Analyzation**	**Grading Criteria**	**Risk Grade**
Robustness	Income and affordability	Income: $51,839 https://www.census.gov/quickfacts/fact/table/chelseacitymassachusetts/INC910217#INC910217 COL: 29% above national average National Income: $57, 652 https://www.ssa.gov/oact/cola/central.html https://www.census.gov/topics/income-poverty/poverty/guidance/surveys-programs.html MA income: $74,167	A - Income is above MA average B - Income is above national average but below MA average C - Income is <10% below national average D - Income is more than 10% below national average	D
Redundancy	Flood insurance	Mandatory flood insurance on marginal St. Zone AE MAP: https://msc.fema.gov/portal/search?AddressQuery=marginal%20st%20chelsea%20ma#searchresultsanchor Saying Zone AE is mandatory insurance purchase: Zone AE definition: Zone AE are areas that have a 1% probability of flooding every year (also known as the "100-year floodplain"), and where predicted flood water elevations above mean sea level have been established. Properties in Zone AE are	A - Above 90% of businesses in a flood prone area have flood insurance or is mandatory. B - Less than 90% of businesses in a flood prone area have flood insurance. C - Less than 75% of businesses in a flood prone area have flood insurance. D - Less than 50% of businesses in a flood prone area have flood insurance.	A

		considered to be at high risk of flooding under the National Flood Insurance Program (NFIP)		
Resourcefulness	Disaster response plan	Mandated by FEMA. Lots of very good info https://www.chelseama.gov/sites/chelseama/files/uploads/cityreviewchelsea_draft_plan_update_5-16-14.pdf	A - City has a plan and funding to deal with any disaster situation. B - City has a plan to deal with minor disaster situations. C - City has a plan to deal with major disaster situations. D - No information is available from the City.	A
Rapidity	Household financial savings	Chelsea: Poverty - 19.5% MA: 10.5%, US: 12.3%, https://www.census.gov/quickfacts/fact/table/chelseacitymassachusetts/INC910217#INC910217	A - The poverty rate is are less than the Mass average B - The poverty rate are above the national average but below MA average C - The poverty rate are <5% above national average D - The poverty rate is more than 5% above national average	D

Appendix H: Initial Design Case

$$30\ Year\ Design\ Water\ Level\ =\ 1.67\ ft$$
$$Average\ Elevation\ Along\ Marginal\ St\ =\ 7\ ft$$
$$Water\ Level\ (DWL)\ =\ 10.8\ ft\ ,(Worst\ Case\ Flooding\ Elevation\ 2050)$$

$$Initial\ Design\ Case$$
$$Depth\ of\ Structure\ Elevation\ =\ 4.5\ ft$$
$$\begin{aligned} Structure\ Crest\ Height\ &= DWL\ -\ Depth\ of\ Structure\ Elevation \\ &=\ 6.3\ ft \end{aligned}$$
$$Design\ Wall\ Height\ =\ 8.7\ ft$$

$$Weight$$
$$Cap\ =\ 7ft\ *0.75\ ft\ = 5.25\ SF$$
$$Concrete\ Blocks\ =\ 2.67\ ft\ *\ 3.5\ ft\ *\ 6\ blocks\ =\ 56.07\ SF$$

$$Total\ SF\ =\ 61.32\ SF$$

$$Assume\ Reinforcement\ =\ 120\ lbs/LF$$

$$\begin{aligned} Total\ Weight\ &= (61.32\ SF\ *\ 150\ lbs/CF)\ +\ 120\ lbs/LF \\ &=\ 9307.5\ lbs/LF \end{aligned}$$

$$\boldsymbol{Bearing\ Capacity}:$$
$$\boldsymbol{q_u = (\frac{c}{tan\phi}) + \frac{1}{2}\gamma_{dry} b\sqrt{K_p}(K_p e^{\pi tan\phi} - 1)}$$
$$\boldsymbol{c = 0}$$
$$\boldsymbol{\phi = 35}$$
$$\gamma_{dry} = \boldsymbol{97\ lb/ft^3}$$
$$\boldsymbol{b(width) = 7}$$
$$\boldsymbol{K_p = tan(45^o + \frac{\phi}{2})^2 = 3.69}$$

$$\boldsymbol{q_u = 21{,}061.15\ lbs/lf}$$

Appendix I: Concrete Sea Wall Low Water Scenario

$$Normal\ Force$$

$$Normal\ Force\ =\ Weight$$
$$=\ 9307.5\ lb/LF$$

$$Friction$$

$$Angle\ of\ Internal\ Friction\ = 35\quad ^{o}$$
$$\mu\ =\ 0.7$$

$$Friction\ =\ Normal\ Force\ *\mu\ =\ 6115.25\ lbs/LF$$

$$Earth\ Forces$$

$$Beta\ (\beta)\ =\ 0\quad ^{o}$$
$$Height\ (HW)\ =\ 8.7\ ft$$
$$Gamma\ (\gamma)\ =\ 97\ lbs/CF$$
$$Ka\ =\ tan\quad ^{2}(45^{o}-\tfrac{1}{2}(35^{o}))$$
$$=\ 0.27$$

$$Earth\ Forces\ =\tfrac{1}{2}*\gamma*HW^{2}*Ka*cos(\beta)$$
$$=\ 991.16\ lbs/LF$$

$$Sliding\ Stability$$

$$Factor\ of\ Safety\ =\ Stabilizing\ \div\ Anti-Stabilizing\ Forces$$
$$Factor\ of\ Safety\ =\ Friction\ \div\ Earth\ Forces$$
$$=\ 6.57$$

$$Overturning\ Stability$$

$$Stabilizing\ Moments\ =\ Weight*Moment\ Arm$$
$$Stabilizing\ Moments\ =\ 9307.5\ lbs/LF\ *\ 3.5\ ft$$
$$=\ 32576.25\ ft-lb/LF$$
$$Anti-Stabilizing\ Moments\ =\ Earth\ Forces\ *\ Moment\ Arm$$
$$Anti-Stabilizing\ Moments\ =\ 991.16\ lb/LF*1.5\ ft$$
$$=\ 1486.74\ ft-lb/LF$$

$$Factor\ of\ Safety\ =\ Stabilizing\ Moments\ \div Anti-Stabilizing\ Moments$$
$$=\ 21.91$$

Appendix J: Concrete Sea Wall Design Water Level and Wave Height

$$External\ Stability$$

$Wave\ Period\ (Hd)\ =\ 2.5\ sec\ for\ 2\ ft\ wave$

$Hb\ =\ water\ depth\ at\ 5\ ft\ *Hd$

$=\ Hs\ +5*Hd*tan(35^{o})$

$=\ 6.47\ ft$

$L\ =\ Wavelength\ at\ Water\ Depth\ hb\ =Ts\sqrt{g*hb}$

$=\ 37.25\ ft$

$$Modifications\ to\ Goda\ Formula$$

$\delta 22=-0.36*(\frac{Bm}{L}-0.12)+0.93*(\frac{hs-d}{hs}-0.6)\ =\ -0.51$

$\delta 2\ =\ 4.9*\delta 22, if\ \delta 22\ \leq\ 0$

$=\ -2.52$

$$\delta 11=0.93*(\frac{Bm}{L}-0.12)+0.36*(\frac{hs-d}{hs}-0.6)\ =\ -0.33$$

$$\delta 1\ =\ \delta 11*20, if\ \delta 11\leq 0$$

$=\ -6.55$

$$\alpha 11=cos(\delta 2)\div cosh(\delta 1), if\ \delta 2\leq 0$$

$=\ -0.00232$

$$\alpha 10=Hd/d, if\ Hd/d\ \leq 2$$

$=\ 0.31746$

$$\alpha 1\ =\ \alpha 10*\alpha 11\ =\ -0.00074$$

$\alpha 2\ =\ Smaller\ of:\quad \frac{hb-d}{3hb}*(\frac{Hd}{d})^{2}\qquad and\qquad \frac{2d}{Hd}$

$=0.000883$

$\alpha^{*}=\ Larger\ of:\quad \alpha 1\qquad and\qquad \alpha 2$

$=\ 0.000883$

Structure Type Modification Factors

$$\lambda 1 = \lambda 2 = \lambda 3 = 1.0, for\ conventional\ vertical\ wall\ structures$$

Pressure Coefficients for Goda

$$\alpha^{*} \ = Same\ as\ Above$$

$$\alpha 1 \ = 0.6 + 0.5 \left(\frac{4\pi hs \div L}{sinh(4\pi hs \div L)} \right) \quad ^{2} = 0.733$$

$$\alpha 2 \ = Same\ as\ Above$$

$$\alpha 3 \ = 1 - \frac{hw - hc}{hs} * \left(1 - \frac{1}{cosh(2\pi hs \div L)} \right) = 0.617$$

Wave Pressures

$$\eta^{*} \ = 0.75 * (1 + cos(\beta)) * \lambda 1 * Hd \ = \ 3\ ft$$

$$P1 \ = \ 0.5 \ * (1 + cos(\beta) * (\lambda 1 * \alpha 1 + \lambda 2 \alpha^{*} cos^{2}(\beta)) * \rho * weight * g \ = \ 91.4\ lbs/ft^{2}$$

$$P2 \ = \ (1 - \frac{hc}{\eta^{*}}) * P1, if\ \eta^{*} > hc$$

$$= \ 18.28\ lbs/ft^{2}$$

$$P3 \ = \ \alpha 3 * P1 \ = \ 56.43\ lbs/ft^{2}$$

$$PU \ = \ 0.5 * (1 + cos(\beta)) * \lambda 3 * \alpha 1 * \alpha 3 * \rho * weight * g * Hd \ = \ 56.36\ lbs/ft^{2}$$

Levels of Uncertainty

$For\ Horizontal\ Force\ (UFH) \ = 0.9$
$For\ Uplift\ Force\ (UFU) \ = \ 0.77$
$For\ Horizontal\ Moment\ (UMH) \ = \ 0.81$
$For\ Uplift\ Moment\ (UMU) \ = \ 0.72$

Wave Forces

$$Horizontal\ Wave\ Force\ (FH) \ = \ UFH * (0.5 * (P1 + P2) * hc + 0.5 * (P1 + P3) * hd)$$

$$= \ 537.57\ lbs/ft$$

$$Wave\ Uplift\ Force\ (FU) \ = \ UFU * \frac{1}{2} PU * B, where \ \ B = 10\ ft$$

$= 217.0016\ lbs/ft$

Earth Forces

$\beta = 0^o$

$Height\ (hw) = 8\ ft$

$\gamma = 97\ lbs/CF$

$Kp = tan^2(45 + \frac{1}{2}\beta) = 3.69$

$$Earth\ Forces = \frac{1}{2} * \gamma * hw^2 * Kp * cos(\beta)$$
$$= 13545.86\ lb/ft$$

Hydrostatic Forces

$$Hydrostatic\ Forces\ (Fhydro) = \frac{1}{2} * \gamma(H_2O) * x^2 = 1238.32$$

Resultant Normal Force

$N = Weight - FU = 9090.498$

Friction

$Angle\ of\ Internal\ Friction = 35^o$

$\mu = 0.7$

$Friction = N * \mu = 6363.35\ lb/ft$

Sliding Stability

$Stabilizing\ Forces = Friction + FE = 19909.21\ lb/ft$

$Anti - Stabilizing\ Forces = FU + Fhydro = 1775.9\ lb/ft$

$$Factor\ of\ Safety = Stabilizing\ Forces/Anti - Stabilizing\ Forces$$
$$= 11.21$$

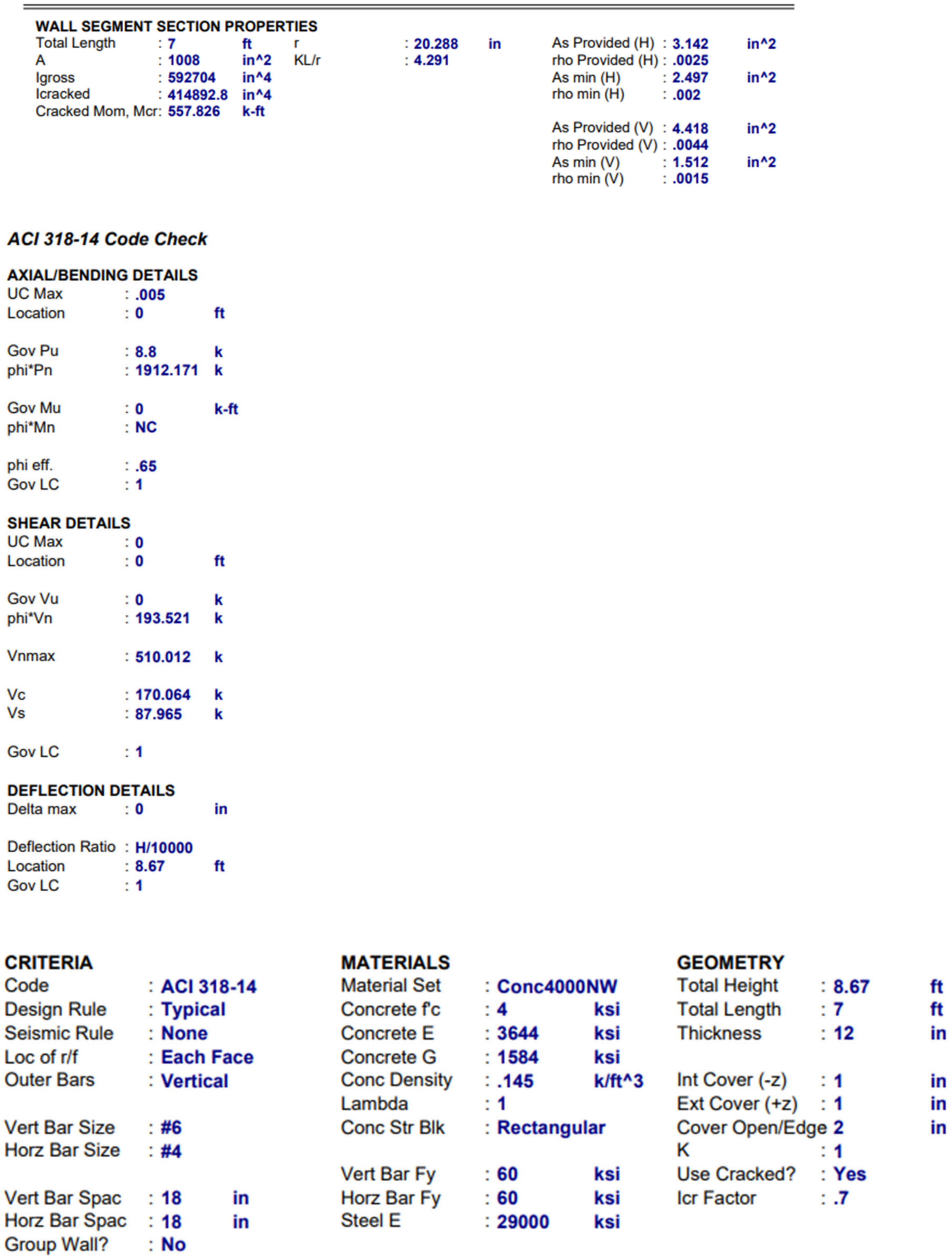
Overturning Stability (about structure heel)

$$Stabilizing\ Moments = (Weight * Moment\ Arm) + (FE * Moment\ Arm)$$
$$= 57548.79\ ft - lbs/ft$$

$$Anti - Stabilizing\ Moments = (FH * Moment\ Arm) + (FU * Moment\ Arm) + (Fhydro * Moment\ Arm)$$
$$= 5068.678\ ft - lbs/ft$$

$$
\begin{aligned}
Factor\ of\ Safety\ &=\ Stabilizing\ Forces/Anti - Stabilizing\ Forces \\
&=\ 11.35
\end{aligned}
$$

Appendix K: Risa 3D Results



```
WALL SEGMENT SECTION PROPERTIES
Total Length       : 7          ft     r        : 20.288   in     As Provided (H)  : 3.142    in^2
A                  : 1008       in^2   KL/r     : 4.291           rho Provided (H) : .0025
Igross             : 592704     in^4                              As min (H)       : 2.497    in^2
Icracked           : 414892.8   in^4                              rho min (H)      : .002
Cracked Mom, Mcr:  : 557.826    k-ft
                                                                  As Provided (V)  : 4.418    in^2
                                                                  rho Provided (V) : .0044
                                                                  As min (V)       : 1.512    in^2
                                                                  rho min (V)      : .0015


ACI 318-14 Code Check

AXIAL/BENDING DETAILS
UC Max          : .005
Location        : 0          ft

Gov Pu          : 8.8        k
phi*Pn          : 1912.171   k

Gov Mu          : 0          k-ft
phi*Mn          : NC

phi eff.        : .65
Gov LC          : 1

SHEAR DETAILS
UC Max          : 0
Location        : 0          ft

Gov Vu          : 0          k
phi*Vn          : 193.521    k

Vnmax           : 510.012    k

Vc              : 170.064    k
Vs              : 87.965     k

Gov LC          : 1

DEFLECTION DETAILS
Delta max       : 0          in

Deflection Ratio : H/10000
Location        : 8.67       ft
Gov LC          : 1


CRITERIA                          MATERIALS                            GEOMETRY
Code          : ACI 318-14        Material Set    : Conc4000NW         Total Height      : 8.67    ft
Design Rule   : Typical           Concrete f'c    : 4       ksi        Total Length      : 7       ft
Seismic Rule  : None              Concrete E      : 3644    ksi        Thickness         : 12      in
Loc of r/f    : Each Face         Concrete G      : 1584    ksi
Outer Bars    : Vertical          Conc Density    : .145    k/ft^3     Int Cover (-z)    : 1       in
                                  Lambda          : 1                  Ext Cover (+z)    : 1       in
Vert Bar Size : #6                Conc Str Blk    : Rectangular        Cover Open/Edge 2           in
Horz Bar Size : #4                                                     K                 : 1
                                  Vert Bar Fy     : 60      ksi        Use Cracked?      : Yes
Vert Bar Spac : 18     in         Horz Bar Fy     : 60      ksi        Icr Factor        : .7
Horz Bar Spac : 18     in         Steel E         : 29000   ksi
Group Wall?   : No
```

Appendix L: Initial Design Case - Alternate

$$30\ Year\ Design\ Water\ Level\ =\ 1.67\ ft$$
$$Average\ Elevation\ Along\ Marginal\ St\ =\ 7\ ft$$
$$Water\ Level\ (DWL)\ =\ 4.82\ ft\ ,(Worst\ Case\ Water\ Elevation\ 2030)$$

$$Initial\ Design\ Case$$
$$Depth\ of\ Structure\ Elevation\ =\ 4.5\ ft$$
$$Structure\ Crest\ Height\ = DWL\ -\ Depth\ of\ Structure\ Elevation$$
$$=\ 0.32\ ft$$
$$Design\ Wall\ Height\ =\ 3.5\ ft$$

$$Weight$$
$$Cap\ =\ 3.5\ ft\ * 0.75\ ft\ = 2.625\ SF$$
$$Concrete\ Blocks\ =\ 2.625\ ft\ *\ 3.5\ ft\ *\ 1\ blocks\ =\ 9.35\ SF$$

$$Total\ SF\ =\ 11.97\ SF$$

$$Assume\ Reinforcement\ =\ 20\ lbs/LF$$

$$Total\ Weight\ = (11.97\ SF\ *\ 150\ lbs/CF)\ +\ 20\ lbs/LF$$
$$= 1815.5\ lbs/LF$$

$$\boldsymbol{Bearing\ Capacity}:$$
$$\boldsymbol{q_u = (\frac{c}{tan\phi}) + \frac{1}{2}\gamma_{dry} b \sqrt{K_p} (K_p e^{\pi tan\phi} - 1)}$$
$$\boldsymbol{c = 0}$$
$$\boldsymbol{\phi = 35}$$
$$\boldsymbol{\gamma_{dry} = 97\ lb/ft^3}$$
$$\boldsymbol{b(width) = 3.5}$$
$$\boldsymbol{K_p = tan(45^o + \frac{\phi}{2})^2 = 3.69}$$

$$\boldsymbol{q_u = 10,530.57\ lbs/lf}$$

Appendix M: Concrete Sea Wall Low Water Scenario - Alternate

$$Normal\ Force$$

$$Normal\ Force\ =\ Weight$$
$$=\ 1815.5\ lb/LF$$

$$Friction$$

$$Angle\ of\ Internal\ Friction\ = 35\ \ ^{o}$$
$$\mu\ =\ 0.7$$

$$Friction\ =\ Normal\ Force\ *\mu\ =\ 1270.84\ lbs/LF$$

$$Earth\ Forces$$

$$Beta\ (\beta)\ =\ 0\ \ ^{o}$$
$$Height\ (HW)\ =\ 3.5\ ft$$
$$Gamma\ (\gamma)\ =\ 97\ lbs/CF$$
$$Ka\ =\ tan\ \ ^{2}(45^{o}-\frac{1}{2}(35^{o}))$$
$$=\ 0.27$$

$$Earth\ Forces\ = \frac{1}{2}*\gamma*HW^{2}*Ka*cos(\beta)$$
$$=\ 160.41\ lbs/LF$$

$$Sliding\ Stability$$

$$Factor\ of\ Safety\ =\ Stabilizing\ \div\ Anti-Stabilizing\ Forces$$
$$Factor\ of\ Safety\ =\ Friction\ \div\ Earth\ Forces$$
$$=\ 7.9$$

$$Overturning\ Stability$$

$$Stabilizing\ Moments\ =\ Weight*Moment\ Arm$$
$$Stabilizing\ Moments\ =\ 1815.5\ lbs/LF\ *\ 1.75\ ft$$
$$=\ 3177.12\ ft-lb/LF$$
$$Anti-Stabilizing\ Moments\ =\ Earth\ Forces\ *\ Moment\ Arm$$
$$Anti-Stabilizing\ Moments\ =\ 160.41\ lb/LF*0.5\ ft$$
$$=\ 80.21\ ft-lb/LF$$

$$Factor\ of\ Safety\ =\ Stabilizing\ Moments\ \div Anti-Stabilizing\ Moments$$
$$=\ 39.61$$

Appendix N: Concrete Sea Wall Design Water Level and Wave Height - Alternate

$$External\ Stability$$

$Wave\ Period\ (Hd)\ =\ 2.5\ sec\ for\ 2\ ft\ wave$

$Hb\ =\ water\ depth\ at\ 5\ ft\ *Hd$

$=\ Hs\ +5*Hd*tan(35^{o})$

$=\ 0.49\ ft$

$L\ =\ Wavelength\ at\ Water\ Depth\ hb\ =Ts\sqrt{g*hb}$

$=\ 37.25\ ft$

$$Modifications\ to\ Goda\ Formula$$

$\delta 22=-0.36*(\frac{Bm}{L}-0.12)+0.93*(\frac{hs-d}{hs}-0.6)\ =\ -0.51$

$\delta 2\ =\ 4.9*\delta 22, if\ \delta 22\ \leq\ 0$

$=\ -2.52$

$$\delta 11=0.93*(\frac{Bm}{L}-0.12)+0.36*(\frac{hs-d}{hs}-0.6)\ =\ -0.33$$

$$\delta 1\ =\ \delta 11*20, if\ \delta 11\leq 0$$

$=\ -6.55$

$$\alpha 11=cos(\delta 2)\div cosh(\delta 1), if\ \delta 2\leq 0$$

$=\ -0.00232$

$$\alpha 10=Hd/d, if\ Hd/d\ \leq 2$$

$=\ 6.25$

$$\alpha 1\ =\ \alpha 10*\alpha 11\ =\ -0.015$$

$\alpha 2\ =\ Smaller\ of:\quad \frac{hb-d}{3hb}*(\frac{Hd}{d})^{2}\qquad and\qquad \frac{2d}{Hd}$

$=0.32$

$\alpha^{*}=\ Larger\ of:\quad \alpha 1\qquad and\qquad \alpha 2$

$=\ 0.32$

$$\mathit{Structure\ Type\ Modification\ Factors}$$

$$\lambda 1 = \lambda 2 = \lambda 3 = 1.0, \mathit{for\ conventional\ vertical\ wall\ structures}$$

$$\mathit{Pressure\ Coefficients\ for\ Goda}$$

$$\alpha^{*} \ = \mathit{Same\ as\ Above}$$

$$\alpha 1 \ = 0.6 + 0.5 \left(\frac{4\pi hs \div L}{sinh(4\pi hs \div L)} \right)^{2} = 1.10$$

$$\alpha 2 \ = \mathit{Same\ as\ Above}$$

$$\alpha 3 \ = 1 - \frac{hw - hc}{hs} * \left(1 - \frac{1}{cosh(2\pi hs \div L)} \right) = 0.99$$

$\mathit{Wave\ Pressures}$

$\eta^{*} \ = 0.75 * (1 + cos(\beta)) * \lambda 1 * Hd \ = \ 3\ ft$

$P1 \ = \ 0.5 \ * (1 + cos(\beta) * (\lambda 1 * \alpha 1 + \lambda 2 \alpha^{*} cos^{2}(\beta)) * \rho * weight * g \ = 176.72\ lbs/ft^{2}$

$P2 \ = \ if\ \eta^{*} < hc$

$\quad = \ 0\ lbs/ft^{2}$

$P3 \ = \ \alpha 3 * P1 \ = \ 176.47\ lbs/ft^{2}$

$PU \ = \ 0.5 * (1 + cos(\beta)) * \lambda 3 * \alpha 1 * \alpha 3 * \rho * weight * g * Hd \ = 136.64\ lbs/ft^{2}$

$$\mathit{Levels\ of\ Uncertainty}$$

$\mathit{For\ Horizontal\ Force}\ (UFH) \ = 0.9$

$\mathit{For\ Uplift\ Force}\ (UFU) \ = \ 0.77$

$\mathit{For\ Horizontal\ Moment}\ (UMH) \ = \ 0.81$

$\mathit{For\ Uplift\ Moment}\ (UMU) \ = \ 0.72$

$$\mathit{Wave\ Forces}$$

$\mathit{Horizontal\ Wave\ Force}\ (FH) \ = \ UFH * (0.5 * (P1 + P2) * hc + 0.5 * (P1 + P3) * hd)$

$\quad = \ 303.76\ lbs/ft$

$\mathit{Wave\ Uplift\ Force}\ (FU) \ = \ UFU * \frac{1}{2} PU * B, where\ \ B = 10\ ft$

$\quad = 526.09\ lbs/ft$

Earth Forces

$\beta = 0^{o}$

$Height\ (hw) = 3.5\ ft$

$\gamma = 97\ lbs/CF$

$Kp = tan^{2}(45 + \frac{1}{2}\beta) = 3.69$

$$Earth\ Forces = \frac{1}{2} * \gamma * hw^{2} * Kp * cos(\beta)$$
$$= 2192.32\ lb/ft$$

Hydrostatic Forces

$$Hydrostatic\ Forces\ (Fhydro) = \frac{1}{2} * \gamma(H_2O) * x^{2} = 3.19\ lbs/CF$$

Resultant Normal Force

$N = Weight - FU = 1289.4$

Friction

$Angle\ of\ Internal\ Friction = 35^{o}$

$\mu = 0.7$

$Friction = N * \mu = 902.58\ lb/ft$

Sliding Stability

$Stabilizing\ Forces = Friction + FE = 3094.91\ lb/ft$

$Anti - Stabilizing\ Forces = FU + Fhydro = 306.95\ lb/ft$

$$Factor\ of\ Safety = Stabilizing\ Forces/Anti - Stabilizing\ Forces$$
$$= 10.08$$

Overturning Stability (about structure heel)

$$Stabilizing\ Moments = (Weight * Moment\ Arm) + (FE * Moment\ Arm)$$
$$= 14277.43\ ft - lbs/ft$$

$$Anti - Stabilizing\ Moments = (FH * Moment\ Arm) + (FU * Moment\ Arm)$$
$$+ (Fhydro * Moment\ Arm)$$
$$= 4291.52\ ft - lbs/ft$$

$$Factor\ of\ Safety = Stabilizing\ Forces/Anti - Stabilizing\ Forces$$
$$= 3.33$$

Appendix O: Contour Map

Light brown-2ft

Dark brown-10ft