Improving Long-Term Coastal Resiliency: A Living Shoreline Design for Chelsea Creek

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

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Sponsor:
The City of Chelsea, Massachusetts

Abstract

The City of Chelsea, Massachusetts is prone to habitual flooding due to low elevation, continued erosion, and a need for improved coastal stabilization infrastructure. In order to protect the vulnerable communities of Chelsea in a sustainable manner, the City is considering the implementation of a living shoreline along a portion of Chelsea Creek alongside the Chelsea Street Bridge. Using a site suitability matrix, comprehensive cost analysis, and review of potential environmental impacts, our team designed a living shoreline consisting of multiple features, such as switchgrass, coir logs, a salt marsh, an oyster sill, and reef balls. In addition, the team outlined an implementation strategy, which included a suggested construction plan, key maintenance concerns, and a permitting analysis.

Acknowledgements

The completion of this project would not have been possible without the help from certain individuals. The team would like to thank Ben Cares and Alex Train from the City of Chelsea for their support and cooperation. The team would also like to extend their thanks to Frank Taormina from the Massachusetts Department of Environmental Protection for providing insight into permitting through an interview. Lastly, the team would like to thank both project advisors from Worcester Polytechnic Institute, Professor Albano and Professor Mathisen, for their guidance throughout the project.

Authorship

This Major Qualifying Project (MQP) was completed by Civil Engineering Undergraduate Students from Worcester Polytechnic Institute (WPI). Every team member had input on each section of the written report, whether through writing or editing. A comprehensive breakdown of the authorship for this report can be seen in Appendix B.

Team member Evan Andrzejewski was responsible for aiding in the completion of the suitability matrix table and conducting in-depth cost analyses for multiple design alternatives. He also helped design the salt marsh that is featured in the complete *SolidWorks* model of the final living shoreline design. For the report, Evan wrote multiple sections pertaining to these topics, as well as other supporting sections throughout.

Team member Peter Conroy was responsible for determining the terrestrial parameters for the project site for the suitability matrix and for researching design methods for bank protection for suitability and cost analysis. For the report, Peter wrote sections on the final design options and the cost versus suitability analysis, as well as part of the Conclusion.

Team member Julie Pham was responsible for designing the final living shoreline and creating the final design visuals such as the infographics, and *SolidWorks* model. For the report, Julie wrote and edited multiple sections in the Methodology and Results.

Team member Jonathan Scribner was responsible for the permitting analysis and implementation strategy. Jonathan was also a leader in the development of the site suitability matrix and cost analysis. For the report, Jonathan wrote the sections pertaining to his focus areas outlined above in addition to writing large sections of the Background and Methodology.

Capstone Design Statement

It is predicted that the Greater Boston Area will be subject to significant sea level rise in the near future due to anthropomorphic climate change. The City of Chelsea, Massachusetts is especially at risk of flooding largely due to its low elevation, but also because of its poorly draining soils and insufficient stormwater management infrastructure (*Proposed Chelsea Creek*, 2021). This project entails developing a living shoreline design for the City of Chelsea to mitigate flooding and erosion along a section of Chelsea Creek by the Chelsea Street Bridge. In order to address this design problem, the team defined the project scope, conducted a literature review of the living shoreline industry, mapped site ecological resource areas and boundaries, evaluated the site compatibility for broad living shoreline alternatives, chose a specific and multifaceted living shoreline alternative, and completed a permitting memorandum detailing boundaries, feasibility, and timeline. The site compatibility for broad living shoreline alternatives was assessed by a comprehensive scoring methodology that the team developed, with the input data based on existing site conditions and future projections for sea level rise. A specific and multifaceted living shoreline alternative was selected through an iterative process based on the compatibility results and the investigation of living shoreline case studies in the Greater Boston Area.

The Accreditation Board for Engineering and Technology (ABET) requires that all students in an accredited engineering program complete a capstone design experience before obtaining an engineering degree. A capstone design experience allows students to demonstrate the technical skills and knowledge acquired through their coursework. To best provide the City of Chelsea with a comprehensive design and to fulfill the Worcester Polytechnic Institute (WPI) capstone criteria for Accrediting Engineering Programs by the ABET, the following realistic constraints were considered: economic, environmental, social and political, ethical, health and safety, constructability, and sustainability. The paragraphs below briefly discuss how each of these constraints was addressed.

Economic:

A cost comparison was conducted across several multi-faceted living shoreline design solutions. The final results of this analysis were defined in units of price per linear foot of shoreline. In order to determine these unit cost values, material, installation, and maintenance costs were considered, along with a review of existing literature on living shoreline costs.

Environmental:

Often engineering projects merely strive to limit negative impacts on the environment, and don't necessarily consider how to create a positive and interdependent interaction between environment and design. This project on living shorelines focuses on both the former and the latter. The natural materials used in living shorelines allow for environmental benefits such as increased biodiversity, improved water quality, and carbon sequestration, but it also poses environmental challenges. For example, planting an invasive rather than a native species would be detrimental to habitat retention and biodiversity. An understanding of the existing environmental conditions and ecological resources was established and factored into the evaluation of living shoreline alternatives.

Social and Political:

Social and political implications were the main reasons that this project was begun. According to the Executive Office of Energy and Environmental Affairs (EEA), Chelsea residents are classified as an environmental justice population, meaning that they are most at risk of being unaware of or unable to participate in environmental decision-making or to gain access to state environmental resources (*Proposed Chelsea Creek*, 2021). The Hispanic and Latino neighborhoods have a high social vulnerability to flooding and have long advocated for improved public access to, and use alongside, Chelsea Creek. This project is part of a reconceptualization of land use along Chelsea Creek from purely industrial to partially recreational. The team addressed the concerns of the Chelsea residents by proposing a design solution that is sustainable and accessible to all.

Ethical:

This project abides by the American Society of Civil Engineers (ASCE) Code of Ethics for all civil engineers to ensure the safety and welfare of the public, protects the reputation of WPI and the City of Chelsea, and to maintains professionalism, honesty, and virtue.

Health and Safety:

The health and safety of the public is the most important design constraint of every civil engineering project. The main goal of this project was to improve coastal resilience and protect the public from sea level rise and increased chance of flooding due to anthropomorphic climate change. The final living shoreline design strives to improve the health of the public by reducing air and water pollution from local industrial operations.

Constructability:

Proper consideration of constructability in the design stages is vital to ensure that the design can be feasibly and practically implemented in a limited amount of time. Even though this project is a part of the City of Chelsea's preliminary design stage, it's still important to frame the design with deliberation on the realistic limits of construction equipment and laborers. Constructability was an aspect of the team's cost comparison between living shoreline design alternatives. In addition, the team developed a permitting memorandum that identifies the boundaries to construction and a timeline for the pre-construction phase.

Sustainability:

Sustainability is at the heart of this project's goals, and it strongly influenced the selection of the final living shoreline design. Living shorelines were selected for this design problem because they are more sustainable than traditional coastal stabilization methods like concrete bulkheads. In the context of this project sustainability not only refers to a living shoreline's ability to rise with the sea level and prevent flooding, but it also encompasses the long-term health of surrounding flora, fauna, and the community. Sustainability in this project also refers to maintenance and monitoring costs, which for living shorelines are large in the short term but very small in the long term. The team considered all aforementioned aspects of sustainability in the final design.

Professional Licensure Agreement

For the past 100 years, the Professional Engineer's (PE) license has been used by states to protect public health, safety, and welfare, and to define the minimum knowledge needed to practice engineering. The civil engineering profession has a distinct skill set that must be obtained through education and experience. The culmination of this process occurs when a state board presents a civil engineer with a Professional Engineering license. A PE license can often create new opportunities for growth and advancement in the workplace. Licensure carries with it responsibility, liability, and privileges that are a very important part of the engineer's career. Unlike their engineering colleagues who are employed in industries that assume product liability for their designs, engineers who offer professional services are regulated by state licensure boards, laws, and regulations (Swenty & Swenty, 2017). Licensed Professional Engineers are the cornerstone of the civil engineering profession.

To become a Professional Engineer, one must complete a time consuming and rigorous process. One must first graduate from an ABET-accredited program, then pass the Fundamentals of Engineering (FE) Exam, accumulate at least four years of experience working under the supervision of a Professional Engineer, and then finally pass the Principles and Practice of Engineering (PE) exam. The FE and PE exams are administered by The National Council of Examiners for Engineering and Surveying (NCEES). Once one passes the FE Exam they officially become a Professional Engineer (PE). However, to maintain the status of a PE, one will have to keep up to date with the latest industry standards and perhaps complete continued education, depending on the state in which their license is awarded.

Executive Summary

The Problem: In recent years there has been a significant increase in sea level and flooding events in Chelsea, Massachusetts. The flooding risk zones predominantly overlay the environmental justice population of Chelsea, which consists of vulnerable, low-income housing. A sustainable coastal stabilization solution is needed to protect the community in the long-term.

Project Goal: The goal of this project was to develop a living shoreline, a coastal flooding and erosion mitigation strategy that utilizes materials such as plants, sand, and/or rock, designed for the City of Chelsea, Massachusetts to mitigate flooding and erosion along a section of Chelsea Creek near the Chelsea Street Bridge.

Methods: In order to accurately portray the site and its needs, background research was gathered and quantitative measurements were made. This information allowed for the team to create multiple matrices that led to a final design recommendation. The objectives associated with this approach are as follows:

<u>Objective 1: Research Literature on Living Shorelines and the State of the Industry</u>

An understanding of the concept of living shorelines, general engineering guidelines, and industry trends was established. Case studies in New England were researched to identify regulatory and environmental implementation barriers of the region.

<u>Objective 2: Characterize the Existing Site Conditions and Analyze Future Projections</u>

A list of design factors was developed to characterize the site, and these factors were organized into five major categories: system, hydrodynamic, terrestrial, ecological, and additional considerations. Quantitative and qualitative data was collected on the design factors through a combination of library research and a site visit.

<u>Objective 3: Create Multiple Design Alternatives for Coastal Stabilization</u>

A site suitability matrix was developed to evaluate the compatibility of common coastal stabilization methods with the project site. Each coastal stabilization method was also subject to a cost analysis, which consisted of a lump-sum value for the material, mobilization, and installation costs plus annual maintenance costs projected to 2070. These methods included marsh sill, breakwater, revetment, living reef, reef balls, beach nourishment, and bank toe protection. Individual coastal stabilization methods were combined to form four design alternatives that complemented each other’s benefits and mitigated each other’s drawbacks.

<u>Objective 4: Identify a Final Design and Analyze Regulatory and Sustainability Implications</u>

A final design alternative was selected through an analysis of the environmental implications, design longevity, possible implementation barriers, and community impact of the

four design alternatives from Objective 3. For the final design, a construction plan, maintenance outline, and permitting analysis were conducted. The key permitting steps, involved agencies, and general timelines for the state and federal permitting processes were detailed.

Recommendations: The final design alternative selected included reef balls on the nearshore area, an oyster sill salt marsh (Spartina Alterniflora) on the shoreline area, two stacked coir logs at the toe of the bank, and vegetation on the bank slope (switchgrass and American beachgrass) and at the top of the bank (saltbush). This final design can be seen below in Figure 1.

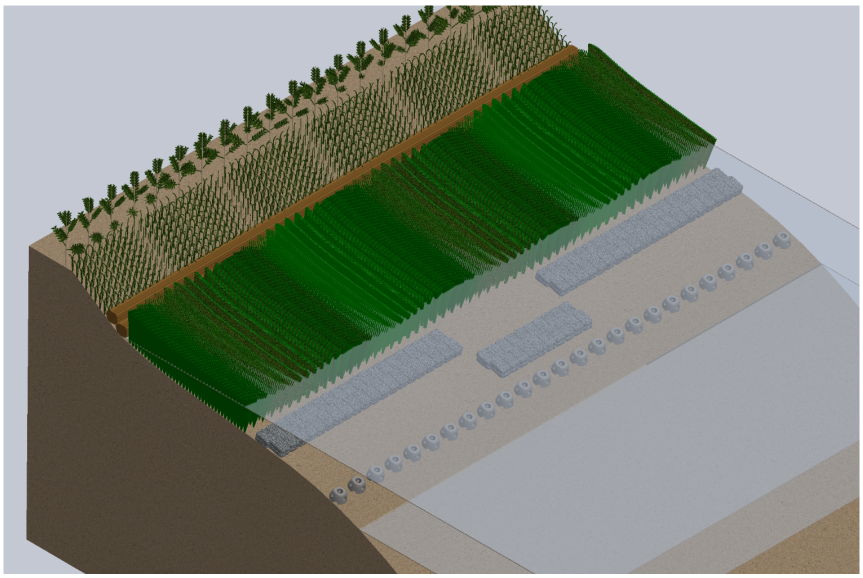

Figure 1: *SolidWorks* Model of Living Shoreline Design.

Permitting Implications

The state permitting process is projected to take four to six months, and the major chronological steps are through the Massachusetts Environmental Policy Act, Wetlands Protection Act, and Massachusetts Public Waterfront Act. The federal permitting process involves acquiring General Permits 5, 7, and 23 from the U.S. Army Corps of Engineers. Both the federal and state permitting processes are exempt from fees for this project.

Living Shoreline Integration with City of Chelsea Plans

The City of Chelsea plans to convert the area upland of the living shoreline into a park or similar dynamic open space. Boardwalks could be placed near or within the living shoreline with posters detailing the functions and environmental benefits of the design elements. Permanent structures near the bank should be avoided to allow for landward migration of the living shoreline over time. Sufficient levels of vegetation or drainage should be maintained to prevent excess stormwater runoff into the living shoreline and creek.

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Abbreviations

BFE - Base Flood Elevation

CSOs - Combined Sewer Overflows

CZM - Coastal Zone Management

DEP - Department of Environmental Protection

DPA - Designated Port Area

ENF - Environmental Notification Form

EPA - Environmental Protection Agency

FEMA - Federal Emergency Management Agency

FIRMS - Flood Insurance Rate Maps

GIS - Geographic Information System

GPs - General Permits

MEPA - Massachusetts Environmental Policy Act

MHW - Mean High Water

MLW - Mean Low Water

MTL - Mean Tide Level

MWRA - Massachusetts Water Resources Authority

NOAA - National Oceanic and Atmospheric Administration

NOI - Notice of Intent

NWPs - Nationwide Permits

PCN - Preconstruction Notification

SLR - Sea Level Rise

SVNF - Self-Verification Notification Form

USACE - United States Army Corps of Engineers

USDA - United States Department of Agriculture

USGS - United States Geological Survey

WPA - Wetlands Protection Act

WPI - Worcester Polytechnic Institute

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1.0 Introduction

The purpose of this study is to determine and design the most effective means to protect an area from sea level rise and catastrophic storms due to climate change, all while prioritizing an environmentally sustainable solution. Climate change and rising sea levels are a threat to coastal communities around the world, especially to the City of Chelsea, Massachusetts. Sources predict that sea levels have risen 0.14 inches per year in recent years and that this rate will only increase (Climate Change: Global Sea Level, 2021). Chelsea is a coastal city that borders Boston with a close-to-sea level elevation city-wide. Chelsea has also been hit with many flood events in recent years, some as a result of over fourteen inches of rainfall, which caused millions in property damage. (City of Chelsea Hazard Mitigation Plan 2014 Update, 2014) Because of these statistics, it is predicted that by 2070, about 50% of the City will see probable flooding during storms (Designing Coastal Community Infrastructure, 2017). Among these, important facilities to not only Chelsea, but the surrounding area, such as the Mass General Hospital could be at risk of flooding in the near future. In addition, the areas likely to be affected by flooding are low-income housing, the ethnicity of which is largely Hispanic. A coastal stabilization system along Chelsea Creek should be addressed immediately in order to protect vulnerable communities and preserve valuable infrastructure.

In order to build coastal resiliency, communities often elect to implement "hard" or "gray" solutions like bulkheads or revetments. While effective at protecting against wave energy and flooding, "hard" coastal stabilization methods have several drawbacks, including: providing a short-term solution to a long-term problem, increased seaward erosion, reflected wave energy, decreased biodiversity, and prevention of habitat migration.

An alternative to "gray" coastal stabilization methods is a living shoreline, which is a "green" approach. For the purposes of this report, living shorelines are defined as "a set of coastal erosion control practices, ranging from non-structural vegetated approaches to hybrid structural natural methods, that address erosion and flooding in a manner that improves or protects the ecological condition of the coastline" (Woods Hole Group, 2017). Examples of hybrid structural-natural methods are oyster reefs, rock sills, or anchored wood. Living shorelines are a long-term solution to climate change, as their elevation rises with the sea level over time by trapping sediments from tidal waters. The environmental benefits of a living shoreline include improved water quality, habitat retention for shallow water fish and wildlife, increased biodiversity, natural marsh migration, and carbon sequestration. These benefits are especially valuable for the City of Chelsea, as they are striving to restore the diverse aquatic life that historically inhabited Chelsea Creek before industrialization.

Project Goal and Key Objectives

The goal of this project was to develop a living shoreline design for the City of Chelsea, Massachusetts to mitigate flooding and erosion along a section of Chelsea Creek just west of the Chelsea Street Bridge, which can be seen below in Figure 2. This goal was accomplished through the following four main objectives:

1) Research literature on living shorelines and the state of the industry
2) Characterize the existing site conditions and analyze future projections
3) Create multiple design alternatives for coastal stabilization
4) Identify a final design and analyze regulatory and sustainability implications

Figure 2: Aerial View of Proposed Living Shoreline Area Alongside the Chelsea Street Bridge.

2.0 Literature Review

Introduction

This literature review serves as a background for not only understanding living shoreline concepts, but also the scope of the project problem. The research presented below includes sea level rise and flooding trends to give a sense of the scale of the project problem. The research also includes relevant historical and cultural conditions of the City of Chelsea in relation to the project. The main portion of this section involves research into the living shoreline industry, engineering guidelines, barriers to implementation, and living shoreline case studies in New England.

2.1 Global Warming and Sea Level Rise

Global warming is defined as "the long-term heating of Earth's climate system" (Climate Change: Global Sea Level, 2021). This trend is mostly due to human activity, which includes the burning of fossil fuels. This process began during the beginning of the industrialization period in the middle to late 19th century. When fossil fuels are burned, the emissions from these reactions are released into the atmosphere, which include compounds such as carbon dioxide. These unnatural levels of carbon dioxide act as an artificial blanket for Earth, as it disallows heat to escape back into space. This ever-thickening layer of emissions within the atmosphere is attributed to a rise of average global temperature of 1.8 degrees Fahrenheit since emissions began (Climate Change: Global Sea Level, 2021). This statistic also works in an exponential manner, so the global average temperature increase rate is projected to increase in the future (Figure 3).

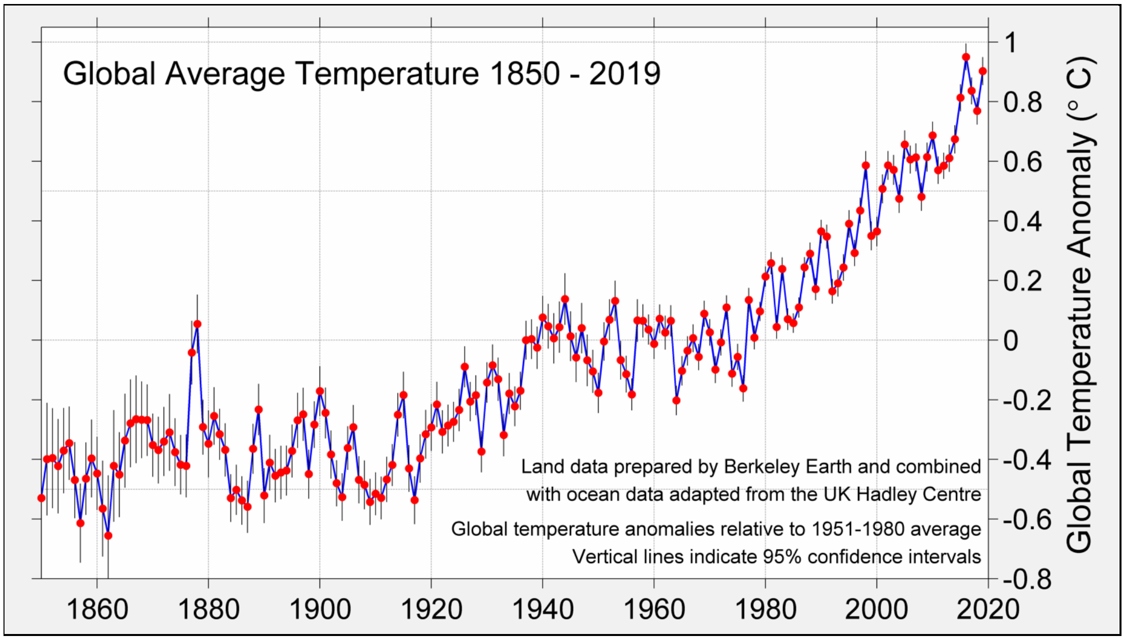


Figure 3: Global Average Temperature Since 1850. (Rhode, 2021)

One side effect of global warming is the melting of Arctic ice. In the past 30 years, ice in the Arctic has declined by 95% (World Wildlife Fund, n.d.). The melting of Arctic ice adds water to the oceans, which in turn causes a rise in sea level. Melting glaciers and ice sheets around the world also add to this sudden rise. It is estimated that, on average, global sea level has risen 8-9 inches since 1880 (Climate Change: Global Sea Level, 2021). Since this phenomenon is directly linked to global warming, the rate of global average sea level rise is also projected to increase in the future (Figure 4).

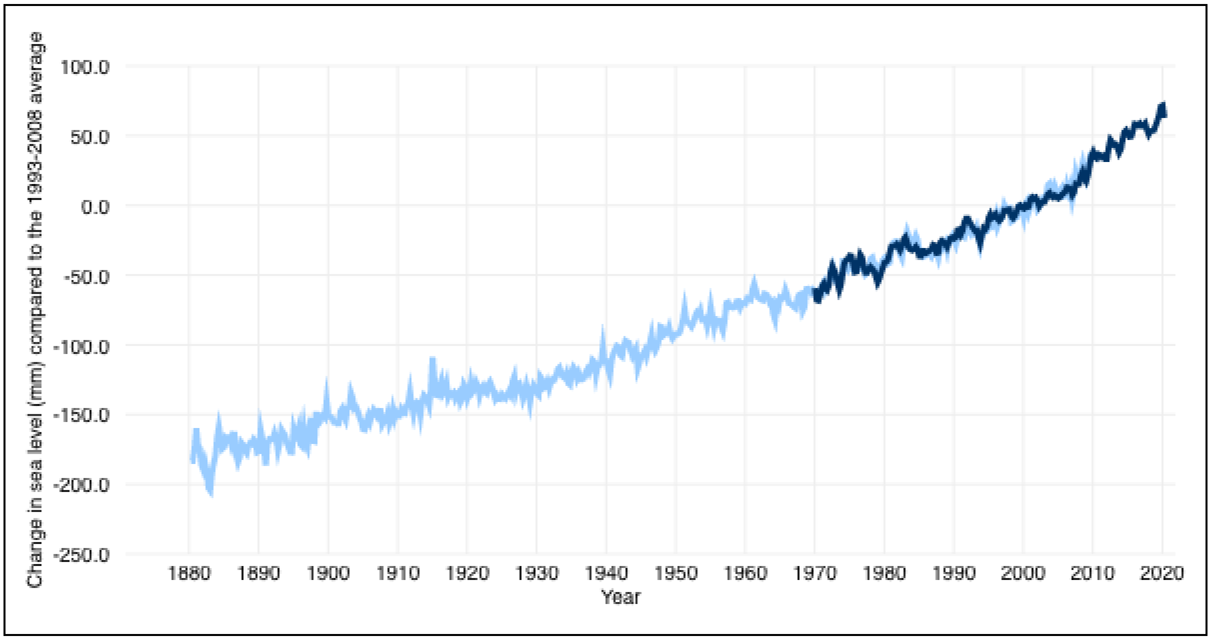


Figure 4: Global Sea Level Since 1880. (Climate Change: Global Sea Level, 2021)

Although this water being added to oceans causes them to rise, the higher temperatures due to global warming also contribute to thermal expansion. When the temperature of an object increases, the molecules that make up that object move around faster and more sporadically, which causes the object to swell in size. Although this change is relatively small, multiplying it across something as large as oceans leads to noticeable and dramatic increases. The light blue line on the graph above represents the estimate of sea level, while the dark blue line is actual sea level data (Climate Change: Global Sea Level, 2021). The similarity in these lines shows that estimates have continued to prove truthful and that these estimates are worth considering.

Coastal communities are severely impacted by global warming and sea level rise. Multiple factors such as proximity to the ocean lead to more frequent and severe flooding, more storms, and a higher water table (U.S. Environmental Protection Agency, n.d.).

2.2 Background on the City of Chelsea

2.2.1 The History of the City of Chelsea

The City of Chelsea, Massachusetts, located across the Mystic River from Boston, has supported the local community for centuries. The land in and around the Chelsea waterfront was first used by Native Americans who hunted and harvested fish and shellfish. In the early 1600's, Europeans began to build permanent settlements in the vicinity of the project area. Throughout the Colonial Period and through the years following the American Revolution, the area was largely farm and pasture land. A tide mill was built near the head of Chelsea Creek in 1721 and the tenant farmers in the area supplied milk and hay to Boston residents and supplied livestock, shellfish, and produce to outgoing vessels (*Proposed Chelsea Creek*, 2021). During the Industrial Period, Chelsea became known for its wooden shipbuilding industry and its oil, paint and varnish manufacturers (Chelsea, nd.).

The population quickly increased post-Civil War as Irish immigrants and Canadians from Nova Scotia began settling into the town (About our city, nd.). Over the next half century, due to its waterfront location and easy access to major cities via railroad, the City of Chelsea became a prime location for rapid industrialization. Manufacturers of rubber goods, paper boxes, and shoes became the city's leading industries. However, accelerated industrialization also led to many devastations, provoking many large fires that harmed the City as well as those living there. The most notable of these events being the Great Chelsea Fire of 1908 that destroyed the city's waterfront, downtown and businesses, leaving many unemployed and over 18,000 people homeless (Chelsea, nd.). Over the course of 100 years, Chelsea endured more than thirty significant fires, which may have had potential effects on the city's ecosystems, wildlife habitats, air quality, and contribute to the increase in greenhouse gas emissions (Lake, C. C., 2011).

In addition to damages from large fires and air pollution, Chelsea is very vulnerable to flooding. The City is bordered by water on three sides, which is roughly 60 percent of its municipal boundary. The water surrounding the City consists of the Island End River, Mill Creek, Chelsea Creek, and the Mystic River (Bongiovanni, 2021). A significant portion of Chelsea's land was developed by filling salt marshes. Sitting at low elevations, these coastal areas are tidally influenced, with high groundwater tables and poorly draining soil. In addition, more recently pollution has reduced the remaining marsh areas along the coast. Therefore, Chelsea currently lacks the natural ability to alleviate flooding (*Proposed Chelsea Creek*, 2021).

The city's old infrastructure and lack of stormwater management also increase the city's flooding vulnerability. (City of Chelsea community resilience building summary of findings, 2018). According to the City of Chelsea Hazard Mitigation Plan 2014, there have been 18 notable flood/storm surges from 1993 to 2014. Over the course of these two decades, coastal flooding and storm surges have caused the City millions of dollars in property damage. One of the most significant flood events occurred in March 2010 where a series of light to heavy rainfall occurred over a five week period. As seen in Figure 5, the eastern portion of Massachusetts received the highest amount of rainfall at the beginning of the rain period, ranging from 7-8 inches. Approximately 10.7 million dollars in property damage was caused (City of Chelsea Hazard Mitigation Plan 2014 Update, 2014). Continued flooding over time will only lead to further damage of the city's infrastructure, destruction of land, and negative impacts on the people of Chelsea.

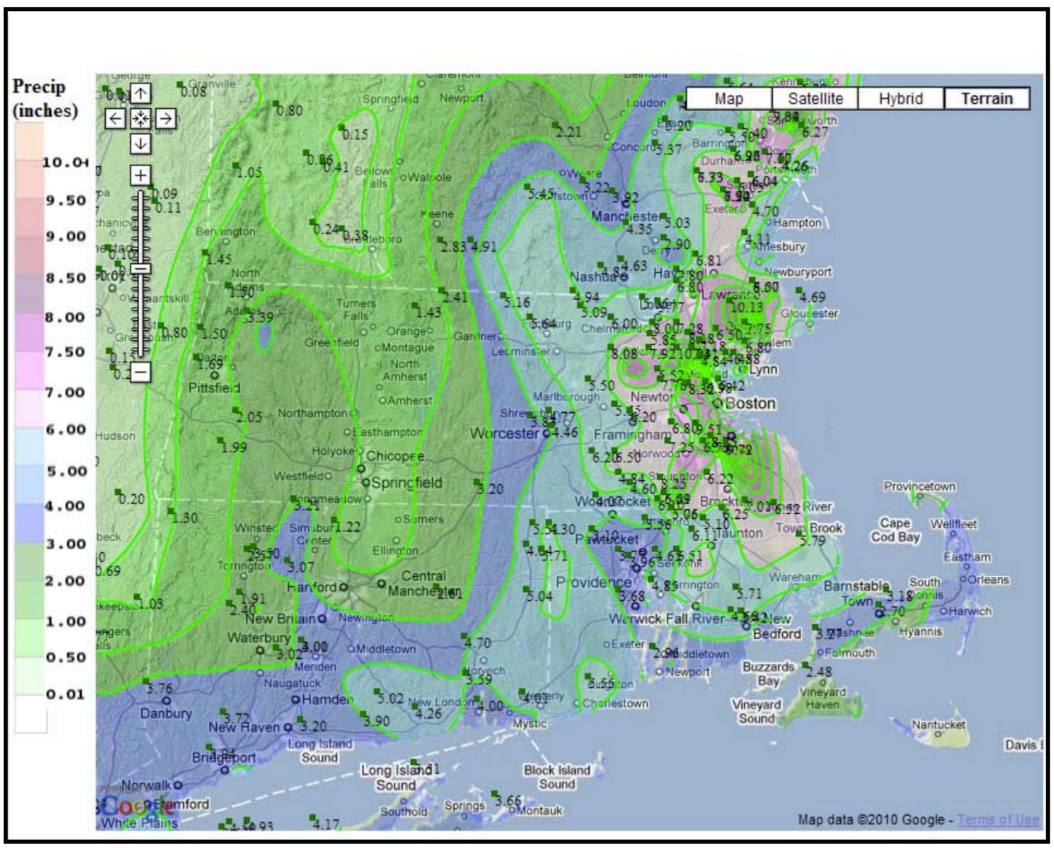


Figure 5. Rainfall in New England from March 13th to March 15th, 2010. (NOAA US Department of Commerce, 2021)

While Chelsea used to have extensive salt marshes and other natural resources, in 2013 it was identified as the third most environmentally-burdened city in Massachusetts (*Proposed Chelsea Creek*, 2021). Oil remains a leading industry in Chelsea, with high demands for petroleum products, regional home heating oil, gasoline and jet fuel for the nearby Logan Airport (About the Chelsea Street bridge project, nd.). While oil products have greatly industrialized the City, it has also led to an increase in air pollution. Chelsea also provides road salt to 350 New England communities. The salt is stored in 50-foot tall piles along Chelsea Creek, much to the dismay of nearby residents. Traffic has become a large issue surrounding the Eastern Massachusetts area, with Route 1 and the Chelsea Street Bridge being the main routes to enter Boston. Vehicle emissions in this area have had significant impacts on the air quality in Chelsea and the health conditions of the people living there. According to the Massachusetts Environmental Public Health Tracking, asthma-related hospital cases have notably increased (City of Chelsea community resilience building summary of findings, 2018).

The Chelsea Street Bridge (Figure 1) is a vertical lift bridge that spans Chelsea Creek and connects Chelsea to East Boston and Logan Airport. The bridge was replaced in 2012 at a high cost to taxpayers, and it was promised that the new bridge would allow larger vessels to service Chelsea Creek. Larger vessels means fewer trips and less frequent bridge openings, thus less traffic congestion. “Nine years later, that promise has not been realized nor is there a plan to realize it” (*Proposed Chelsea Creek*, 2021). Due to the high traffic of cargo carrying-vessels, the bridge opens an average of five to six times a day. To further compound the problem, the bridge openings are not scheduled ahead of time to allow commuters to plan their trips.

2.2.2 The City of Chelsea’s Demographics

Chelsea has a population of approximately 40,000 people (Bureau U.S.C., 2021). Considering the City has only 2.1 square miles of land, it is densely populated, as are most suburbs outside of larger cities. 67% of people in Chelsea identify as Hispanic or Latino, which is the second largest percentage of such ethnicity in Massachusetts, behind the town of Lawrence (Bureau, U.S.C., 2021). The specific spots of settlement may tie into the fact that this group of people have a higher social vulnerability to flooding (Climate Central). For example, as shown in Figure 6, the only section of Chelsea that is not predominantly Hispanic or Latino is not prone to flooding due to the area’s higher elevation. The majority of the area affected by flooding is low-income housing that is close to the shoreline or at particularly low elevations (Figure 7). In the future these communities will be at an even higher risk as the prediction of probable flooding is slated to increase (Designing Coastal Community Infrastructure, n.d.). Likely as a result of poor environmental conditions from industrial activity, Chelsea residents also have high rates of lead poisoning, cancer, asthma, and cardiovascular disease. Chelsea residents are classified as an environmental justice population, meaning that they are most at risk of being unaware of or unable to participate in environmental decision-making or to gain access to state environmental resources (*Proposed Chelsea Creek*, 2021).

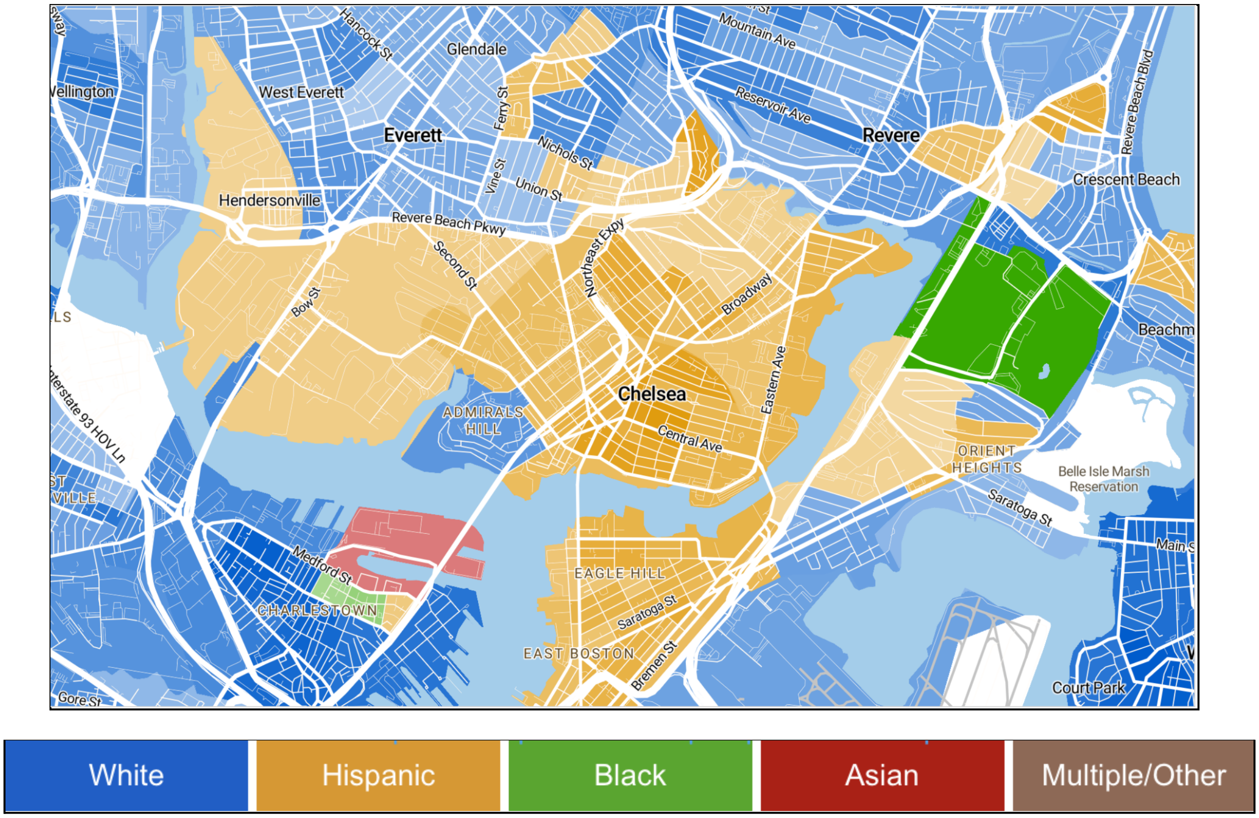


Figure 6: Race Population Map for Chelsea, MA. (Race Map for Chelsea, MA and Racial Diversity Data, n.d.)

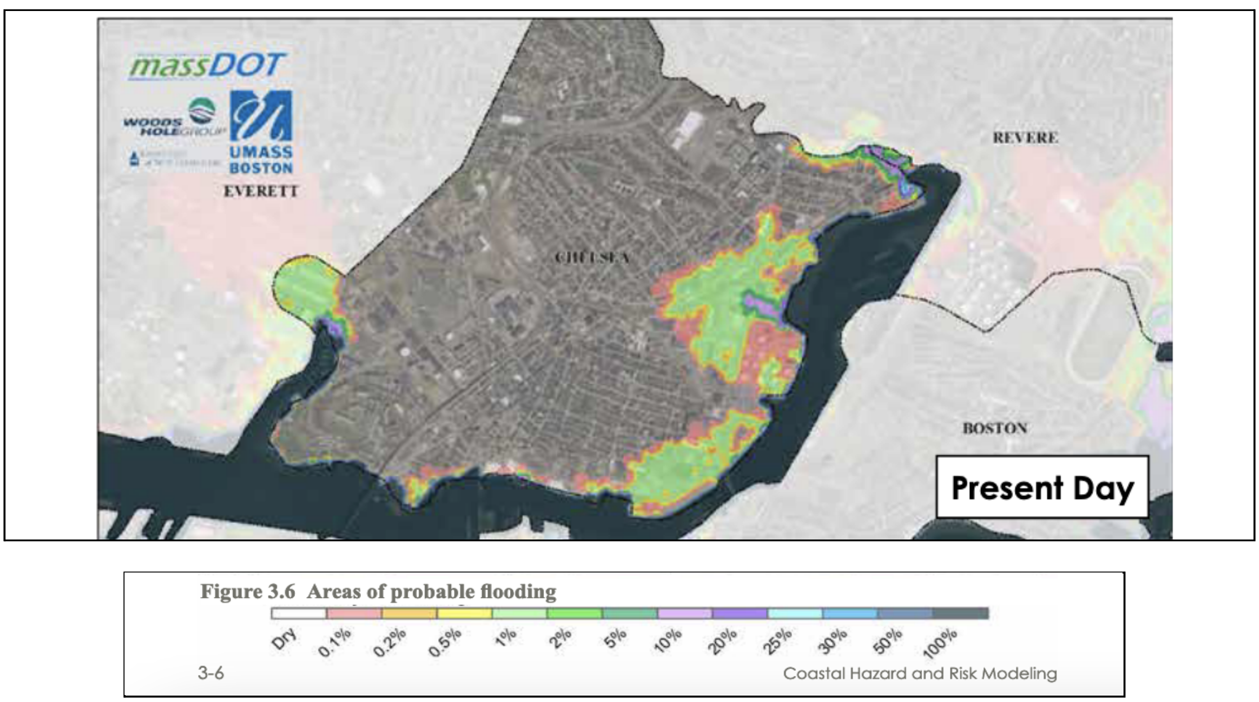


Figure 7: Present Day Flooding Risk for Chelsea, MA. (Designing Coastal Community Infrastructure, n.d.

2.2.3 General Information on Chelsea Creek

Chelsea Creek is a 1.8 mile long, highly engineered, tidal river. Its waterfront mostly consists of active industrial activities and underutilized land contaminated by past industrial use, as seen in Figure 8. Chelsea Creek serves the commercial needs in Chelsea, East Boston, and Revere, and has seen an increase in large vessel traffic over the last several years. The channel is currently 38 feet deep and approximately 225-250 feet wide from the McArdle Bridge to the Chelsea Street Bridge. From the Chelsea Street Bridge to a point near the creek's end, the channel is 250-430 feet wide. The Boston Harbor Improvement Project plans to further deepen and widen Chelsea Creek to accommodate large vessels, but currently there is no funding or scheduling for the project. Chelsea Creek faces water quality issues, largely from polluted runoff. The City of Chelsea has an impervious cover of 75% and very little green space. Because of this, Chelsea Creek receives stormwater inputs containing urban contaminants from runoff in Chelsea, East Boston, Revere, and Everett (*Proposed Chelsea Creek*, 2021).

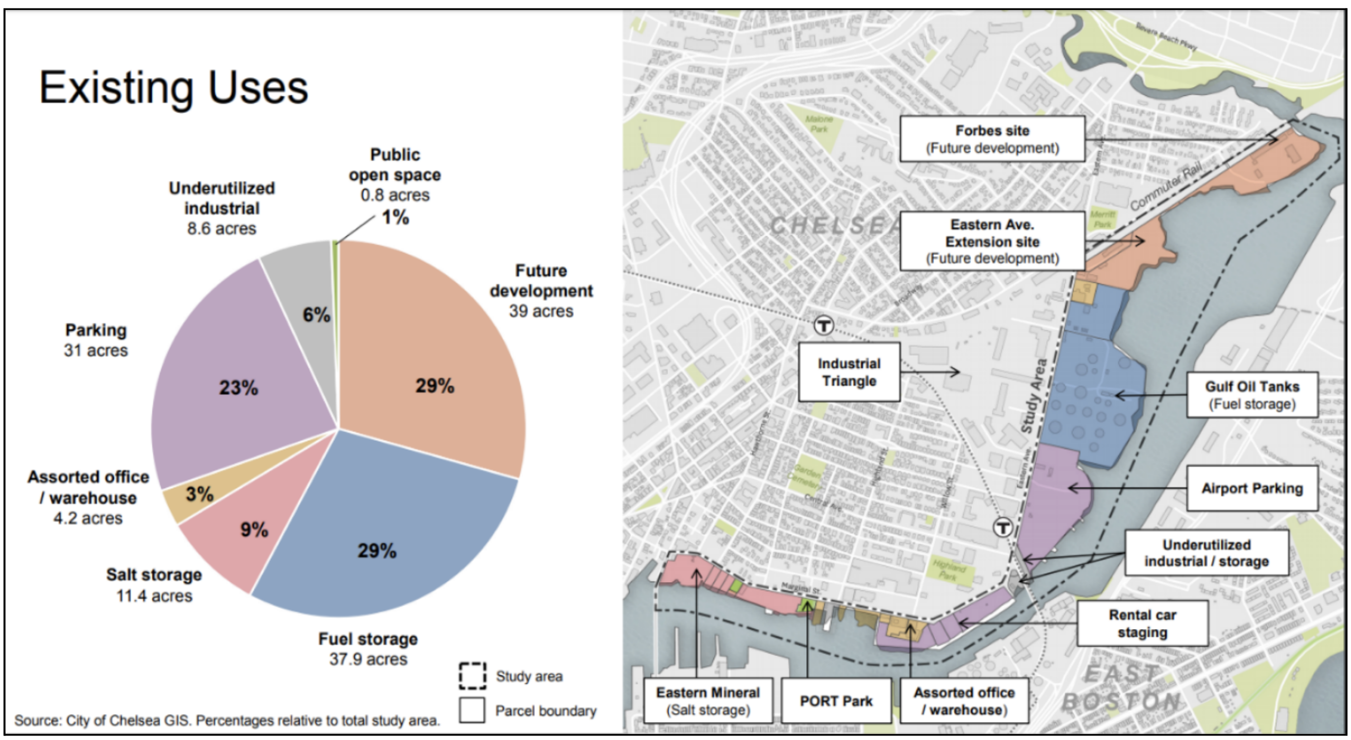


Figure 8: Existing Land Uses Along Chelsea Creek Waterfront. (*Proposed Chelsea Creek*, 2021)

Public and environmental action around Chelsea Creek has been high for the last decade. Local communities feel they have been long prevented from rightful access to the creek’s waterfront due to the industrial nature of the region. The City of Chelsea has plans to create multiple points of access along the creek filled with public art, temporary retail, and public programming. Some of the ideas for these initiatives include pop-up markets, seasonal retail, outdoor movies and entertainment, and food trucks (*Proposed Chelsea Creek*, 2021). With the declining health of the natural shoreline of Chelsea Creek and increased chance of flooding with sea level rise, there have been numerous reports and meetings between public and private stakeholders around building the city's climate resiliency. It is evident from these reports and meetings that multi-faceted and sustainable solutions are needed for Chelsea Creek's shorelines.

2.3 What is a Living Shoreline?

Living shorelines, also known as "green shores" or "ecologically enhanced shorelines", are a green infrastructure approach to shoreline protection contrary to traditional "hard" shoreline stabilization measures such as bulkheads and revetments. Originally developed in the Chesapeake Bay area two decades ago, living shorelines have gradually gained momentum and spread nationwide (Miller et al., 2015). Living shorelines are created by planting native wetland plants, wetland grasses, shrubs, and trees at various points along a shoreline (U.S. Department of Commerce, 2019). While attempting to mimic the habitat of a natural shoreline as closely as possible, living shorelines typically differ from natural shorelines in two elements. One being that living shoreline plantings are done on a grid, making the initial plant density controlled by design not flooding. The second element is that living shorelines have a constant gradual slope, while natural shorelines often have an eroded edge and complex microtopography (Mitchell, 2019). Living shorelines can be installed on freshwater and saltwater coasts, wherever erosion is present (Living Shorelines, 2021). In addition to resisting erosion, living shorelines have the ability to adapt to rising water levels and increased storm activity by trapping sediments from tidal waters. In areas with high wave energy, organic materials such as fiber mats and oyster shells can serve as breakwaters and reduce the energy to an acceptable level for the native vegetation.

Living shorelines can be developed using natural components, but in some cases a hybrid system is needed. Natural living shorelines are typically used in lower energy environments, such as estuaries or lakes. They include native vegetation like marsh grasses and reefs, and biodegradable materials like logs made from coconut fibers. On the other hand, hybrid living shorelines are used in lower to moderate energy environments, like bays or some open-ocean coastline. Hybrid systems have both “soft” (natural) and “hard” (manmade) components. They can incorporate native vegetation or biodegradable organic materials with low-profile rock structures or bulkheads (Living Shorelines, n.d.).

2.4 Living Shorelines vs. Structural Shorelines

When it comes to coastal flooding mitigation, there are many different strategies to keep water away from desired areas. Traditionally, structures made of concrete or stone were built to act as a wall against a body of water. A bulkhead, a vertical wall placed next to a body of water designed to hold soil in behind it and keep water out in front of it, falls into this category (Fisheries, NOAA, n.d.). This structure can also counteract erosion. A revetment is another common fix in coastal communities, which acts like a wall but uses boulders or riparian instead and lays on the shoreline itself (Fisheries, NOAA, n.d.). This material can also be extended into the ocean in order to create a breakwater, which disrupts tidal patterns in an effort to lessen the blow of waves and currents on the shoreline. These strategies can be classified as coastal structures.

On the other hand, living shorelines can achieve the same goals but with sustainability at the forefront of design. Living shorelines provide a “green” alternative to “gray” shoreline stabilization methods like revetments or bulkheads. A spectrum of “green” to “gray” shoreline stabilization approaches, and their general intended use, can be seen in Figure 9.

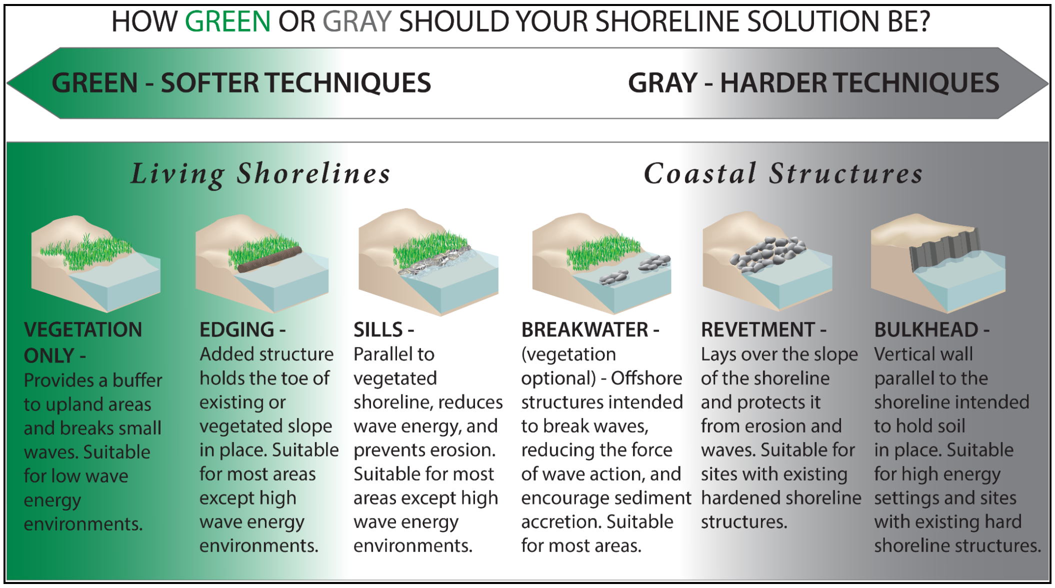


Figure 9: "Green" to "Gray" Spectrum of Shoreline Stabilization Methods. (*NOAA's Living Shorelines engagement*, n.d.)

Living shorelines are dynamic with the surrounding environment, unlike bulkheads which are static systems and thus short-term solutions to climate change. Marshes trap sediments from tidal waters, allowing them to raise their elevation with the sea level and thus prolong their effectiveness as a shoreline stabilization method. Living shorelines encourage natural marsh migration, while hard shoreline structures prevent sediment collection and may create seaward erosion. In addition, living shorelines are generally more cost effective for construction and in the long-term, as they are self-sufficient once developed and don't require costly repairs or additions like bulkheads. According to a comprehensive study on material costs, living shorelines range from \$50–\$150 per linear foot based on the type of living shoreline. By comparison, the same analysis for bulkheads produced a cost range of \$80–\$1200 per linear foot (Living Shorelines, n.d.). Another major benefit of living shorelines is that they absorb wave energy, rather than reflecting it like bulkheads. Reflected wave energy results in scour offshore of the system, deepening of the water, and loss of offshore vegetation (U.S. Department of Commerce, 2016). Other benefits of living shorelines include improved water quality, habitat retention for shallow water fish and wildlife, increased biodiversity, and carbon sequestration. One square mile of salt marsh can store the carbon equivalent of 76,000 gal of gas annually (U.S. Department of Commerce, 2019). Water quality is improved because the roots of the living shoreline plants filter and slow harmful runoff from adjacent lands, thus reducing the amount that reaches the body of water.

While the advantages of a living shoreline approach are numerous, their disadvantages should be explored as well. The major drawback of living shorelines is that their effectiveness is largely dependent on the existing environment. For example, living shorelines are not effective for steep-sloped or deep water coastlines, or coasts consistently exposed to high wave energy. In addition, living shorelines require larger areas of land as compared to hard shoreline stabilization methods, thus often resulting in a more complicated permitting process. Living shorelines also require extensive planning and environmental knowledge prior to construction, because questions such as the following need to be addressed: What is the native soil type? What wildlife are in the existing area? How much foliage or fill needs to be kept/removed/added? Which plants need more sunlight?, and Which areas stay dry or wet? It is important to note that living shorelines are engineered systems and thus they frequently contain structures designed to mitigate wave energy, which can disrupt sedimentation and faunal settlement patterns (Mitchell, 2019). Finally, while living shorelines are self-sustaining in the long term, it takes two to three years of costly and time-consuming maintenance like fertilizing and replanting to ensure the system is growing appropriately (U.S. Department of Commerce, 2016).

2.5 Engineering Guidelines for Living Shoreline Design

As previously mentioned, the effectiveness of living shorelines to control erosion and act as a barrier to sea level rise is largely dependent on the site conditions. Different types of living shorelines will be more suitable depending on the project, and in some cases a living shoreline approach may have to be abandoned altogether. In addition, living shoreline projects are usually diverse, thus each project may have its own set of unique factors to consider.

When determining a project's shoreline stabilization method, system, ecological, hydrodynamic, and terrestrial parameters should be taken into account, along with additional considerations like permitting and constructability. Professionals in the Davidson Laboratory Center for Maritime Systems at Stevens Institute of Technology extensively analyzed each set of parameters, defining their importance in determining a shoreline stabilization approach and also providing quantitative ranges for each factor to streamline the decision-making process (Miller et al., 2015). The system parameters that these professionals established were erosion history, sea level rise, and tidal range. Ecological parameters consisted of water quality, soil type, and sunlight exposure. Hydrodynamic parameters covered wind waves, wakes, currents, ice, and storm surge. Terrestrial parameters included upland slope, shoreline slope, width, nearshore slope, offshore depth, and soil bearing capacity. Additional considerations were permits and regulations, end effects, constructability, native and invasive species, debris impact, and project monitoring (Miller et al., 2015). The appropriate conditions for various living shoreline approaches and the consequent criteria ranges can be seen below in Figure 10 and Figure 11, respectively.

	Marsh Sill	Breakwater	Revetment	Living Reef	Reef Balls
System Parameters					
Erosion History	***Low-Med***	***Med-High***	***Med-High***	***Low-Med***	***Low-Med***
Relative Sea Level	Low-Mod	Low-High	***Low-High***	Low-Mod	Low-Mod
Tidal Range	***Low-Mod***	Low-High	Low-High	***Low-Mod***	Low-Mod
Hydrodynamic Parameters					
Wind Waves	***Low-Mod***	***High***	***Mod-High***	***Low-Mod***	***Low-Mod***
Wakes	***Low-Mod***	***High***	***Mod-High***	***Low-Mod***	***Low-Mod***
Currents	Low-Mod	Low-Mod	Low-High	Low-Mod	Low-Mod
Ice	***Low***	***Low-Mod***	***Low-High***	***Low***	Low-Mod
Storm Surge	Low-High	***Low-High***	***Low-High***	Low-High	Low-High
Terrestrial Parameters					
Upland Slope	Mild-Steep	Mild-Steep	***Mild-Steep***	Mild-Steep	Mild-Steep
Shoreline Slope	***Mild-Mod***	***Mild-Steep***	**Mild-Steep**	***Mild-Mod***	Mild-Steep
Width	***Mod-High***	***Mod-High***	Low-High	***Mod-High***	***Mod-High***
Nearshore Slope	***Mild-Mod***	***Mild-Mod***	Mild-Steep	***Mild-Mod***	***Mild-Mod***
Offshore Depth	Shallow-Mod	Mod-Deep	Shallow-Deep	Shallow-Mod	Shallow-Mod
Soil Bearing	Mod-High	***High***	***Mod-High***	Mod-High	***Mod-High***
Ecological Parameters					
Water Quality	Poor-Good	Poor-Good	Poor-Good	***Good***	***Poor-Good***
Soil Type	***Any***	Any	Any	Any	Any
Sunlight Exposure	***Mod-High***	Low-High	Low-High	Mod-High	Low-High

Figure 10: Engineering Parameter Conditions for Various Living Shoreline Designs. (Miller et al., 2015)

	Criterion		
Parameter	Low/Mild	Moderate	High/Steep
System Parameters			
Erosion History	<2 ft/yr	2 ft/yr to 4 ft/yr	>4 ft/yr
Sea Level Rise	<0.2 in/yr	0.2 in/yr to 0.4 in/yr	>0.4 in/yr
Tidal Range	< 1.5 ft	1.5 ft to 4 ft	> 4 ft
Hydrodynamic Parameters			
Waves	< 1 ft	1 ft to 3 ft	> 3 ft
Wakes	< 1 ft	1 ft to 3 ft	> 3 ft
Currents	< 1.25 kts	1.25 kts to 4.75 kts	>4.75 kts
Ice	< 2 in	2 in to 6 in	> 6 in
Storm Surge	<1 ft	1 ft to 3 ft	>3 ft
Terrestrial Parameters			
Upland Slope	<1 on 30	1 on 30 to 1 on 10	>1 on 10
Shoreline Slope	<1 on 15	1 on 15 to 1 on 5	> 1 on 5
Width	<30 ft	30 ft to 60 ft	>60 ft
Nearshore Slope	<1 on 30	1 on 30 to 1 on 10	>1 on 10
Offshore Depth	< 2 ft	2 ft to 5 ft	> 5 ft
Soil Bearing Capacity	< 500 psf	500 psf - 1500 psf	> 1500 psf
Ecological Parameters			
Water Quality	-	-	-
Soil Type	-	-	-
Sunlight Exposure	<2 hrs/day	2 to 10 hrs/day	>10 hrs/day

Figure 11: Data Ranges for Different Engineering Parameter Conditions. (Miller et al., 2015)

Most of the factors above are self-explanatory in terms of their significance with living shorelines, but some are more obscure. The parameters with less obvious impacts on living shoreline design are briefly explained below.

Tidal range, a system parameter, is key for submerged or low structures such as sills or small breakwaters. The position of the top of the structure relative to the water level plays a role in the amount of energy dissipation and thus the amount of force on the structure. Tidal ranges are also important for the selection of the appropriate vegetation and the growth of reef elements like mussels and oysters (Miller et al., 2015). In addition, tidal ranges have a significant effect on a site's sediment supply, as large tidal ranges can result in large sediment fluxes and supplies. Due to rapid sea level rise, some living shorelines may need augmented sediment supplies. One method for doing this is a thin-layer dredge disposal, where a thin deposit of sediment is sprayed over the shoreline in the hope that it will grow the existing marsh. However, this method has only been used on natural marshes, and its effectiveness on living shorelines needs to be studied (Mitchell, 2019).

The hydrodynamic parameters wind waves, boat wakes, and currents are critical in determining the living shoreline type for a project. The size of wind waves are determined by wind speed, wind duration, and the open water distance over which it acts, or fetch. In most coastal engineering applications, the maximum expected wave is used for design. However, the maximum expected wave may not represent the critical condition for living shorelines because a large storm could submerge the entire project. As boats pass, two distinct types of wake waves are generated. Divergent waves, typically generated by large and slow moving ships, are from the bow of the boat. Transverse waves, typically generated by small and fast moving ships, are from the stern and propellers. The largest wakes are generated at the point where the two types of waves intersect. Unfortunately, "wakes are rarely...taken into account during design in a physically satisfying manner, due to a lack of readily available wake measurements" (Miller et al., 2015). Currents are particularly critical for living shoreline sites located near tidal inlets or along riverbanks. Currents have the capacity to uproot vegetation, scour the bank, and transport debris during storms or ice in areas subject to freezing, thus increasing the scour potential (Miller et al., 2015).

Terrestrial parameters such as width, nearshore slope, and soil bearing capacity demand significant attention when designing a living shoreline. Along developed coastlines, the width, or horizontal space between the developed area and the water's edge, is often reduced or eliminated. Large available project widths are conducive to the long-term success of living shorelines, as they provide more potential for upland marsh retreat (Mitchell, 2019). However, when space is not available, two options exist for creating it. The first is to landscape back into the site at an appropriate slope, and the second is to build out the shoreline through the use of fill. In most states, there are strict regulations prohibiting the placement of fill below the mean high water line. Fortunately, the "Living Shorelines General Permit 24 provides an exception for wetland restoration projects...for the purposes of habitat enhancement" (Miller et al., 2015). A site's nearshore slope determines the behavior of the waves and currents immediately offshore. Steeper slopes generally reflect energy, while milder slopes tend to absorb and dissipate energy. In addition, steep nearshore areas will require more fill and may also make structures less stable. Soil bearing capacity is an often overlooked factor in the design of living shorelines projects. The majority of living shoreline projects are constructed in areas with poor soil conditions according to traditional construction standards. Even though the size of the materials used in living shorelines projects is small compared to traditional "hard" stabilization approaches, the additional load imposed by stone, concrete, or even natural reefs needs to be taken into consideration to avoid undesired settlement (Miller et al., 2015).

One ecological parameter is sunlight, which is vital to the development of both aquatic and terrestrial habitats. Photosynthesis only occurs in the presence of sunlight, which directly affects water quality and the level of aquatic and terrestrial biological production (Miller et al., 2015). Shade from trees can not only slow habitat development and migration, but can also raise competition from invasive species (Mitchell, 2019).

2.6 Living Shoreline Permitting Process

The permitting process for living shorelines has historically been complicated and largely dependent on the region of implementation. However, in 2017, the U.S. Army Corps of Engineers authorized Nationwide Permit 54 to make the construction of living shorelines easier across the United States. The conditions for creating a living shoreline under permit 54 are that the project cannot extend more than 500 feet along the shoreline, cannot extend more than 30 feet below the mean low water level, structural materials must be anchored to prevent relocation, native plants appropriate for site conditions should be used with a minimum necessary discharge, there should be minimal adverse effects to water and organism movement, and the living shoreline must be properly maintained. The permit can be obtained from the local U.S. Army Corps of Engineers office in the district (Woods Hole Group, 2017).

Nationwide Permits (NWPs) are a category of General Permits administered by the U.S. Army Corps and traditionally updated every five years. General Permits can be designed and issued at a state scale, a regional scale, or a national scale. Permit conditions vary between states because they can add specific considerations to General Permits “so that they can be more quickly processed and approved, minimizing the burden on both the applicant and the regulators” (Woods Hole Group, 2017). The boards in Massachusetts that may be involved with regulation and review are the Local Conservation Commission, Massachusetts Division of Fisheries and Wildlife (Natural Heritage and Endangered Species Program), Massachusetts Environmental Policy Act Office, and Massachusetts Office of Coastal Zone Management.

2.7 Living Shoreline Case Studies in New England

Living shorelines have been used all across the United States, but they have been extensively used in the Chesapeake Bay area in Maryland. Their construction has been encouraged by the state in order to help stop shoreline erosion and help stem the impacts of flooding. Originally hard methods of stopping soil erosion, like bulkheads and seawalls, were used. However, due to the fact that they reflect the wave energy outward they continued to cause erosion and did not stop the issue. “In 2008, the Maryland Legislature passed the Living Shoreline Protection Act, requiring shoreline property owners to use natural solutions to prevent erosion unless they can prove that such methods would not work on their property” (Maryland’s ‘Living Shorelines’, n.d.). In passing this act, Maryland switched to using soft methods of shoreline erosion prevention that don't reflect the wave energy but absorb and disperse it, as well as help to root sand and sediment in place.

There have also been several different types of living shorelines implemented across New England. There have even been potential living shoreline ideas proposed and planned for the local Chelsea area. The Vision Chelsea Creek project had a proposed plan for the implementation of a living shoreline on an area along the Chelsea Creek. The plan was a detailed assessment of the potential to implement specific types of living shorelines, including shoreline restoration, which is good evidence that similar projects have been researched and considered for the local

Chelsea area. In Middletown, Rhode Island, a natural marsh style living shoreline was created at a site on Sachuest Point. It was able to be planted, but needed maintenance on fences to protect against grazing geese for much of the winter. In addition, in order to deal with ice a gentler slope for the marsh would be beneficial as well as incorporating more shrubs and tall plants which would help to break up the ice (*Living Shorelines,* 2017).

A project in Stratford, Connecticut used a certain type of living breakwater design called reef balls (Figure 12). Reef balls are fiberglass molds filled with concrete that help foster aquatic life, which is most commonly oyster colonies in New England. The concrete used to make reef balls features W.R. Grace's Force 10,000 micro silica, which essentially creates a super high strength and abrasion resistant concrete that has a pH similar to natural sea water. Reef Balls are a very durable wave dissipation method, as they have an expected life of at least 500 years. Reef ball sizes, the orientations of holes in the mold, and anchoring methods depend on a site's level of wave energy (*Reef Ball Brochure & Key Features Page*, n.d.). The Stratford site showed that the tidal range needs to be carefully considered with reef balls, as the oysters may freeze and die if they are exposed out of the water too long in the winter (*Living Shorelines in New England,* 2017).

Figure 12: Reef Ball Breakwater in Stratford, Connecticut. (*Living Shorelines in New England,* 2017)

A study of increasing coastal resiliency and mitigating shoreline erosion at Coughlin Park was conducted in 2016 by Woods Hole Group. Coughlin Park is located on the bayside of Winthrop Barrier in Winthrop Massachusetts, which is just east of Boston's Logan Airport. The study researched the existing conditions at the site and proposed several entirely green and hybrid living shoreline designs. For each design alternative, advantages and disadvantages were presented. For example, the idea of using cobble berms was suggested, which would involve using mounds of cobble at the toe of the coastal bank (Figure 13). The loose cobble would help to break apart the wave energy and would also be able to move slightly, allowing itself to adjust to natural patterns in the water. There are also negatives with its loose structure, mainly that it will require maintenance and some replacement of the cobble as some will be lost over time. They also looked into the use of coir logs, which are rolls of coconut fiber, at the toe of the beach to add a buffer between the toe of the beach and incoming wave energy. This helps stabilize the bank and makes it easier for plant life to grow in the area. The drawbacks of this approach are because the coirs are biodegradable, they will naturally break down rather quickly, with an expected lifespan of five to eight years depending on the wave energy of the site (*A Plan to Increase Coastal Resiliency at Coughlin Park*, 2016).

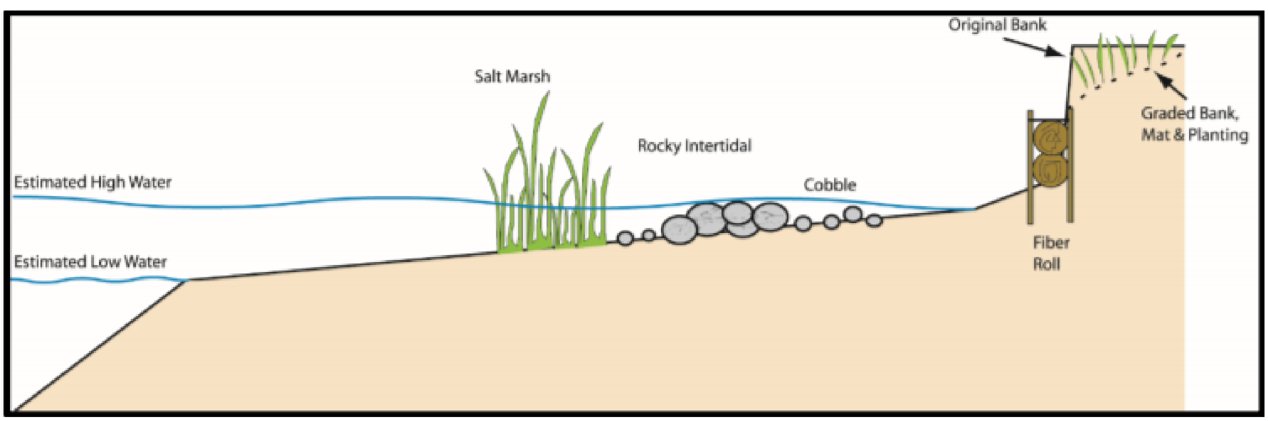


Figure 13: Diagram of Living Shoreline Design at Coughlin Park with Cobble and Coir Rolls. (*A Plan to Increase Coastal Resiliency at Coughlin Park,* 2016)

The Coughlin Park case study highlighted the importance of a multi-faceted approach to living shoreline design in order to address all design factors. Their final design consisted of a combination of fiber rolls, bank grading and planting, cobble bank nourishment, and cobble berm. This case study also detailed an interagency coordination meeting that was held on-site to discuss the project. The agencies in attendance were the Massachusetts Department of Marine Fisheries, Coastal Zone Management, Massachusetts Department of Environmental Protection, Winthrop Conservation Commision, Winthrop Department of Public Works, US Army Corps of Engineers, Woodard and Curran, and Woods Hole Group. The large number of public and private entities involved in this project illustrates how crucial interagency collaboration and consideration of multiple perspectives is when reconstructing a shoreline. It also underscores the complexity of settling on a final design that satisfies environmental, engineering, and public needs (*A Plan to Increase Coastal Resiliency at Coughlin Park*, 2016).

All of the information presented in this literature review was used to determine how the site would be characterized. The engineering guidelines and case studies from this literature review served as a basis for the selection of certain living shoreline techniques. The review of the living shoreline industry and permitting implications gave the team a general understanding of implementation barriers and key agencies to target later in the project.

3.0 Methodology

3.1 Introduction

The goal of this project was to develop a living shoreline design for the City of Chelsea, Massachusetts to mitigate flooding and erosion along a section of Chelsea Creek near the Chelsea Street Bridge. In order to achieve this goal, we:

1) Researched literature on living shorelines and the state of the industry
2) Characterized the existing site conditions and analyzed future projections
3) Created multiple design alternatives for coastal stabilization
4) Identified a final design and analyzed regulation and sustainability implications

The details of each strategy are outlined below.

3.2 Objective 1: Research Literature on Living Shorelines and the State of the Industry

Before laying out the potential shoreline solutions for the Chelsea Street Bridge parcel, an understanding of the concept of living shorelines, general engineering guidelines, and industry trends was established. For example, a holistic summary of the advantages and disadvantages of living shorelines provided a base knowledge necessary for trying to maximize the design benefits and minimize the design drawbacks. In addition, environments generally conducive for certain types of living shorelines were identified. This data served as a reference point later in the project when selecting design alternatives based on collected data. It was critical to have knowledge of the scope of engineering guidelines for living shorelines projects, regardless of type. Furthermore, a list was formulated detailing the key "do's" and "don'ts" in living shoreline design. Additional information collected through research of the concept of living shorelines included planting considerations, maintenance, and permitting.

Once the concept of living shorelines was understood, research on the state of the living shoreline industry, from both a global and regional scale, was begun. This research step was essential to ensure an understanding of current industry trends. This information gave us a broad sense of the feasibility of the project and major barriers to address. Sources such as the National Oceanic and Atmospheric Administration (NOAA) and Woods Hole Oceanographic Institution were used to further the understanding of which parameters were necessary to analyze on the site (NOAA, n.d.; Woods Hole Group, 2017). First, a brief literature review was conducted of the history, progression, and future trends of the global industry. General cost comparisons between different living shorelines systems and between living shorelines and “hard” coastal stabilization methods were obtained. Major barriers to living shoreline implementation, such as strict coastal regulations, were identified. Government and private funding sources were also researched, along with public acceptance. Once an understanding of the global industry was established, the research focus was shifted to the New England area. The level of funding and acceptance of living shorelines in this region was analyzed through case studies in Massachusetts and nearby locations. The results of these studies revealed common design methods and challenges unique to New England, which were implemented in this project’s design.

3.3 Objective 2: Characterize the Existing Site Conditions and Analyze Future Projections

Insight into general living shoreline advantages and disadvantages, the benefits and limitations of different designs, engineering guidelines, and state of the industry were gained through Objective 1. For Objective 2, the research of engineering guidelines was used to develop a list of design factors to focus on for the site. This objective also involves how data was obtained for each factor. When designing a living shoreline, a wide range of factors need to be considered. Factors were organized into five major categories: system, hydrodynamic, terrestrial, ecological, and additional considerations. These categories were developed by individuals in Davidson Laboratory at Stevens Institute of Technology and presented in a report named “Living Shorelines Engineering Guidelines”, which was prepared for the New Jersey Department of Environmental Protection in 2015 (Miller et al., 2015). This report also lists means to obtain data for design parameters, as it presents “level 1” (desktop) analyses and “level 2” (more comprehensive) analyses for each parameter. Several websites and softwares recommended by this source were used, which are highlighted in the results section of this report.

The key system parameters that were examined include erosion history, sea level rise, and tidal range. For data on erosion history, online geographical information programs were available for public use. These programs included *Google Earth*, Nationwide Environmental Title Research (NETR) database, GIS Data Repositories, and the NOAA Lidar Dataset. These programs were used to obtain satellite imagery, historic aerial photographs, and topographic maps and observed the land over the course of many years. From this data, areas that may need more protection from flooding than others were identified. For the sea level rise parameter, data on the sea level projection was obtained online using Risk Finder (*Climate Central,* n.d.). This website was able to provide data reports for the average sea level in 2021 as well as maps of the predicted flooding areas and sea level rise for the next several years. Lastly, for tidal range data, the NOAA Tides and Currents Bench Mark Sheet was used. This sheet records the mean high water, mean sea level, and mean low water in Chelsea Creek in 2002. To obtain a more accurate and updated measurement of the tidal range, Meridian Associates' parcel map prepared for the Commonwealth of Massachusetts in 2021 was analyzed to determine the creek's tidal range (Meridian Associates, 2021).

The key hydrodynamic parameters in the design include wind waves, wakes, currents, and storm surge. To first analyze wind waves, data relating wind speed and direction to conjured wave height was researched. Data for this parameter was found using online databases such as *Windfinder* or the Beaufort Scale (*Windfinder*, n.d.; Recon, n.d.). The Beaufort Scale is an empirical measurement that relates wind speed to observed conditions, allowing for an estimate in wave height (Figure 14).

Force	Wind (Knots)	WMO Classification	Appearance of Wind Effects	
			On the Water	On Land
0	Less than 1	Calm	Sea surface smooth and mirror-like	Calm, smoke rises vertically
1	1-3	Light Air	Scaly ripples, no foam crests	Smoke drift indicates wind direction, still wind vanes
2	4-6	Light Breeze	Small wavelets, crests glassy, no breaking	Wind felt on face, leaves rustle, vanes begin to move
3	7-10	Gentle Breeze	Large wavelets, crests begin to break, scattered whitecaps	Leaves and small twigs constantly moving, light flags extended
4	11-16	Moderate Breeze	Small waves 1-4 ft. becoming longer, numerous whitecaps	Dust, leaves, and loose paper lifted, small tree branches move
5	17-21	Fresh Breeze	Moderate waves 4-8 ft taking longer form, many whitecaps, some spray	Small trees in leaf begin to sway
6	22-27	Strong Breeze	Larger waves 8-13 ft, whitecaps common, more spray	Larger tree branches moving, whistling in wires
7	28-33	Near Gale	Sea heaps up, waves 13-19 ft, white foam streaks off breakers	Whole trees moving, resistance felt walking against wind
8	34-40	Gale	Moderately high (18-25 ft) waves of greater length, edges of crests begin to break into spindrift, foam blown in streaks	Twigs breaking off trees, generally impedes progress
9	41-47	Strong Gale	High waves (23-32 ft), sea begins to roll, dense streaks of foam, spray may reduce visibility	Slight structural damage occurs, slate blows off roofs
10	48-55	Storm	Very high waves (29-41 ft) with overhanging crests, sea white with densely blown foam, heavy rolling, lowered visibility	Seldom experienced on land, trees broken or uprooted, "considerable structural damage"
11	56-63	Violent Storm	Exceptionally high (37-52 ft) waves, foam patches cover sea, visibility more reduced	
12	64+	Hurricane	Air filled with foam, waves over 45 ft, sea completely white with driving spray, visibility greatly reduced	

Figure 14: The Beaufort Scale. (Beaufort, 1805)

Due to project time constraints and limited resources, quantitative data on boat wakes was not obtained via an on-site measurement. Instead, quantitative data on boat wakes was estimated using multiple databases. The first step was to research how vessel size and speed relate to the waves it forms. The government study "Wake Up? Slow Down?" was used as a guide for this step (Knowing your boat, 2015). It was found that there are other factors that affect wake size, such as depth of channel and hull shape. Next, the team researched the typical types of vessels that pass through the Chelsea Creek on a regular basis and the frequency at which this happens. The erosion caused from boat wakes was also derived using the magnitude and direction of estimated wakes, as mitigating this is an area of focus in the shoreline design process. It should be noted that the constraints of this project only allowed us to obtain a sample size of data that does not exactly characterize all boat wakes. For currents, general data was obtained from online sources like the NOAA, NYHOPS, and USGS, where detailed hydrodynamic models exist (Massachusetts. Tides & Currents). General statistics such as direction of flow and speed of current were noted. The effects of this on erosion was also considered. Finally, the last parameter examined was storm surges, which are typically overlooked when designing a living shoreline due to its low positioning. Existing information, like the FEMA Flood Information Study reports and Flood Insurance Rate Maps (FIRMS), provided a general analysis of the storm surges (*OpenFEMA*, n.d.). Other resources such as the NOAA were used to provide estimates of extreme water levels that don't take into account wave effects (Miller et al., 2015).

The key terrestrial parameters in the design were upland slope, shoreline slope, nearshore slope, offshore depth, and site width. For the slope factors located above the water level (upland slope and shoreline slope), relatively accurate and readily available information exists online. Topographic maps, including the Meridian Associates parcel map and digital elevation models (DEMs) were used to find data for these factors (Meridian Associates, 2021). For the slope factors located below the water level (nearshore slope and offshore depth), detailed topographic data was not available. The nearshore slope was found using the shipping channel charts available from the NOAA (Coast Survey., 2012) and the offshore depth was found from the "Proposed Chelsea Creek Municipal Harbor Plan and DPA Master Plan", which included Chelsea Creek's most recent dredging project (Proposed Chelsea Creek Municipal Harbor Plan and DPA Master Plan, 2021). Site width, the horizontal space between the developed area and the water's edge, was obtained through both a physical measurement on a site visit and by using the measure tool on *Google Earth*.

The key ecological parameters were water quality, sunlight exposure, and soil type. Water quality is graded based on factors like dissolved oxygen concentrations, water temperature, salinity, and turbidity (Miller et al., 2015). Several publicly available water quality reports in Boston Harbor were used, including the "2020 Mystic River Watershed Report Card", the "Proposed Chelsea Creek Municipal Harbor Plan and DPA Master Plan", and the "2004-2008 Mystic River Watershed Water Quality Assessment" (EPA Mystic River Report Card, 2020; Proposed Chelsea Creek Municipal Harbor Plan and DPA Master Plan, 2021; Carr, 2010). Sunlight exposure was estimated by using *Google Earth* to take inventory of surrounding infrastructure and vegetation. These results were checked by a field survey during the site visit. The average sunlight per day per season for Chelsea, Massachusetts was also used to assess the sunlight exposure parameter. Soil type, an important but often overlooked factor, requires a multi-faceted analysis in order to have a full understanding of soil strength and behavior. In an ideal scenario, several soil samples could have been collected from different areas on-site to test their physical properties. A hand penetrometer could have been used on-site to estimate soil bearing capacity, or direct shear tests could have been performed back at the WPI laboratories. Unfortunately, the combination of unavailable laboratory equipment and project time constraints rendered this process not viable. As a result, less time-consuming analyses were conducted. First, during the site visit, pictures were taken of the different soil types and general physical properties were noted. Second, the USDA Web Soil Survey Tool was used to collect data on properties like erosion factors, organic matter, soil susceptibility to surface sealing and compaction, depth to any restrictive soil layer, and soil slippage potential (Soil Survey Staff, n.d.). Third, available published geotechnical studies and dredging records for Chelsea Creek near the site location were reviewed.

Additional considerations include exploring regulations and permits, native and invasive species for the area, constructability, sustainability, community impact, and project monitoring. While most of these aspects were considered at this stage of the project, a more detailed analysis was conducted in Objective 4 when picking a final design alternative. For example, it was important to identify native and invasive species for the site at this point in the project, but overall design sustainability could not be determined until specific design combinations were developed. For native and invasive species, pictures were taken of the existing vegetation and wildlife during the site visit. These pictures were compared to a list of non-native plant species with potential for invasiveness in Massachusetts from the Massachusetts Invasive Plant Advisory Group (*The Evaluation of Non-Native Plant Species for Invasiveness in Massachusetts,* 2005). The Massachusetts Department of Environmental Protection list of common native species used in environmental restoration projects was also used (*Wetlands information,* n.d.). When on-site, pictures were taken of the adjacent lands to the project area. How the living shoreline will tie into adjacent lands and the possible negative consequences if the living shoreline fails were questions considered later in the design process. Constructability is largely dependent on other site design factors like tide range, water depth, distance from shore, slope, site access, and permitting requirements. Throughout design, especially in Objective 3, it was kept in mind that generally upland construction is the most cost effective. Project monitoring is also an important factor when choosing between living shoreline design alternatives. Creating a summary of maintenance time and cost from different literature for each living shoreline type was established in Objective 3 as well.

3.4 Objective 3: Create Multiple Design Alternatives for Coastal Stabilization

After identifying the key characteristics of the site and projecting future conditions, multiple design solutions for coastal stabilization were developed and compared. First, the qualitative and quantitative data from Objective 2 was placed into a rough site suitability matrix established by Woods Hole Group (Figure 15). The "Living Shorelines Applicability Index" was developed in 2017 by professional experts from Woods Hole for the Nature Conservancy, a global environmental organization headquartered in Virginia. This Excel-based tool provides a series of pull-down options that can be used to characterize a site's existing conditions. These pull-down options include energy state, existing environmental resources, nearby sensitive resources, tidal range, elevation, intertidal slope, bathymetric slope, and erosion. Based on the requirements of each type of living shoreline, the tool ranks the projected success of each living shoreline as "likely", "possible", or "unlikely" for that site (Woods Hole Group, 2017). The suitability index was designed to provide a useful foundation for the planning stages of living shoreline projects, and it was used as such. The tool was used to both eliminate completely unsuitable design solutions and to provide a reference point for upcoming detailed analyses.

Site Specific Characteristics								
Site Name	Energy State	Existing Environmental Resource	Nearby Sensitive Resources	Tidal Range	Elevation	Intertidal Slope	Bathymetric Slope	Erosion

Living Shorelines Applicability Matrix									
Living Shoreline Type	Energy State	Existing Environmental Resources	Nearby Sensitive Resources	Tidal Range	Elevation	Intertidal Slope	Bathymetric Slope	Erosion	Living Shoreline Type is Applicable to Site?
Dune - Natural	0	0	0	0	0	0	0	0	Unlikely
Dune - Engineered Core	0	0	0	0	0	0	0	0	Unlikely
Beach Nourishment	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Coastal Bank - Natural	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Coastal Bank - Engineered Core	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Natural Marsh Creation/Enhancement	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Marsh Creation/Enhancement w/Toe Protection	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Living Breakwater	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

Figure 15: Woods Hole Preliminary Living Shorelines Applicability Index. (Woods Hole Group, 2017)

Next, a new suitability matrix was created to evaluate the compatibility of common coastal stabilization methods with the project site. This was essentially a more comprehensive version of the Woods Hole “Living Shorelines Applicability Index”. Seven different coastal stabilization approaches were considered: marsh sill, breakwater, revetment, living reef, reef balls, beach nourishment, and bank protection. While most of these approaches are “green” solutions, revetments and breakwaters are more traditional, or “gray”, approaches. These traditional strategies were considered due to a clear theme from the literature review; some sites may demand a hybrid coastal stabilization strategy, with both “green” and “gray” solutions.

The first step in developing this matrix was to establish general scoring ranges for each of the fifteen design parameters, which were grouped into system, hydrodynamic, terrestrial, and ecological. Three scoring ranges were created for low/mild conditions, moderate conditions, and high/steep conditions. These condition ranges are not site specific and are applicable to any location within coastal New England. All of the scoring ranges developed were quantitative, except the ranges for water quality and soil type, as these parameters require consideration of multiple properties. For example, water quality was analyzed by considering pH, turbidity, dissolved oxygen levels, salinity, bacterial contamination, and overall ability to support aquatic life. The main source of information for these scoring ranges was Stevens Institute of Technology “Living Shoreline Engineering Guidelines” (Miller et al., 2015). The quantitative value ranges presented within this document were developed from combining literature and engineering experience. If these values contrasted with information from the literature review in Objective 1, further research was conducted and figures were adjusted accordingly.

After the general condition ranges were established for the suitability matrix, a scoring system was established so that a final score could be attributed to each coastal stabilization strategy for the project site. For each of the seven coastal stabilization measures, the typically suitable condition level, low/mild, moderate, and high/steep, was assigned for each design parameter. For example, salt marshes need sunlight in order to be sustainable, so for the design parameter “sunlight exposure” for the coastal stabilization measure “marsh sill”, the assigned condition level would be “moderate to high”.

Once the condition levels were assigned to each coastal stabilization method, the scoring system was established. A scoring scale of zero to three points was used. A score of zero means that the site data is outside of the general limits by more than 25%. A score of one means that the site data is outside of the general limits by 10% to 25%. A score of two means that the site data is outside of the general limits by less than 10%. A score of three means that the site data is within the general limits. Design parameters have varying importance towards the selection process of different coastal stabilization measures, thus certain design parameter scores within each coastal stabilization strategy were given a multiplier. Two different multipliers were established for the suitability matrix. A design parameter's score was doubled if its compliance was important to the success of the coastal stabilization measure on a particular site. A design parameter's score was tripled if its compliance was vital to the success of the coastal stabilization measure on a particular site. For example, a living reef needs at least good water quality to survive, so it is denoted as a critical design parameter and the score is given a multiplier of three. These multipliers were developed based on a review of professional expertise case studies in New England from the literature review.

Once the scoring system was finalized, the suitability of each coastal stabilization design alternative for the Chelsea, Massachusetts site was evaluated by scoring the site data obtained in Objective 2. Because the number of weighted parameters varied between different design alternatives, the final scores for the seven alternatives were evaluated as a percentage of the total possible weighted score. Higher scores denoted a more suitable alternative, while lower scores denoted a less suitable alternative. It should be noted that the design alternatives scored at this stage were discrete, meaning that combinations of different alternatives were not yet considered.

Once all of the individual design alternatives (marsh sill, breakwater, revetment, living reef, reef balls, beach nourishment, and bank protection) had been scored, the cost was analyzed. Some of these strategies were broken down further into subsections. For example, both rip rap and oyster shell sills were considered for protecting the salt marsh. In addition, bank protection included bank grading and planting costs, as well as different strategies for toe protection. Lastly, costs were obtained for rip rap and oyster shell breakwaters. In order to accurately estimate cost for each of these strategies, costs were individually calculated in terms of raw material, mobilization, installation, and maintenance. This allowed the team to create realistic expectations in terms of initial cost as well as long-term cost. The cost of each design element was calculated by multiplying the cost per unit (ex. $/cubic yard) by the required number of units, according to the dimensions of the project site. Maintenance costs were quantified per year or per a number of years. Therefore, the final cost estimate for each individual design alternative consisted of a lump sum value of the material, mobilization, and installation costs plus a yearly maintenance cost. Some examples of sources that were used to obtain cost data include Gorham Sand and Gravel, New England Wetland Plants, Inc., and the Reef Ball Foundation (6 to 12 inch rip-rap, 2021; *Shrubs*, 2018; *Molds,* n.d.). Other case studies that detail completed projects were also used in reference to gain perspective on the total cost of certain cost factors. One study compiled a complete cost breakdown for a Spartina Alterniflora marsh sill in Louisiana (Louisiana State University, 2007).

Once immediate and maintenance costs were established for each design alternative, the total projected cost for a project during the years 2022-2070 was plotted against the design alternative's site suitability (as a percentage). The year 2070 was selected because it coincides with the timeline used for the sea level rise projections for the site. The results of this graph served as a foundation in the development of the multi-faceted design solutions. The key benefits and drawbacks to each coastal stabilization method, obtained from the literature review, were organized into tables. Environmental implications, design longevity, possible implementation barriers, and community input and impact were evaluated. Possible design combinations were identified when certain designs either complemented each other's benefits or mitigated each other's drawbacks. In addition, more research was conducted on the outcomes of living shoreline projects in New England to pinpoint specific design combinations that could be applicable to the site. Cost was considered in the development of the living shoreline design combinations, but due to this project being in the planning stages, suitability was paramount in the decision-making process.

3.5 Objective 4: Identify a Final Design and Analyze Regulatory and Sustainability Implications

The cost, suitability, and sustainability analyses for the design alternatives created in Objective 3 were used to decide upon a final design. Shop drawings were created for the final design using the *SolidWorks* software, which was available through Worcester Polytechnic Institute. The shop drawings detailed the locations of each design element, planting arrangements, site grades and dimensions, and ecological resource areas. In addition, for each design element an infographic was created to present information in a concise manner. For example, the infographics for the plants included the scientific and common names, root depth, vegetation height and spread, spacing, soil tolerance, and growth rate.

An implementation strategy was developed for the final living shoreline design. The recommendations in this strategy centered around selecting suppliers for each design element, identifying seasonal planting times, establishing the order of design element installation, and identifying construction impacts on the community and constructability concerns. Suppliers were selected based on minimizing costs and maximizing community involvement in the installation process. The surrounding road network and land uses were analyzed to assess the impact of construction mobilization on the community, especially residential areas. Constructability was evaluated by taking into account equipment size and weight, ease of access to the site, tidal ranges, and shoreline soil stability. The implementation strategy also encompassed the maintenance aspect of the living shoreline. An outline of the maintenance plan for each design element was provided, as well as an estimate of the time until the entire living shoreline would be self-sustaining. Maintenance costs such as fertilizer, replanting, addition of fill and materials, and debris removal were considered.

The final design's sustainability and potential impacts, both positive and negative, on the surrounding environment were analyzed. Using projected sea level rise and flooding data, an approximation of the system's potential longevity was concluded. The compatibility of the plant species used in the living shoreline and species in adjacent lands were investigated. Negative implications of the final design were explored thoroughly by applying knowledge gained from the literature review and the New England case studies within. Potential living shoreline co-benefits, like carbon sequestration, would be identified as well.

The main focus of Objective 4 was to conduct a permitting and regulatory analysis of this living shoreline project. Regulatory and permitting barriers were explored from the federal, state, and local levels. The first step in the permitting analysis was to identify key agencies and regulations that pertained to the activities similar to that of living shorelines. This step included finding any applicable regional and federal environmental mandates and programs. Then, interviews were conducted with professionals in the Massachusetts regulatory field to gain a deeper understanding of the previously researched policies. The main point of these interviews was to get a chronological sense of the permitting process for activities in waterways. The interviews helped to focus the analysis to only regulations and permits that applied to the project site. The end product of the permitting analysis was a list of necessary permits the City of Chelsea needs to obtain for this project, the feasibility of being granted certain permits, the order that the permit applications must be completed, and an approximate time frame for the permitting process.

4.0 Results

Introduction

This section first details the site measurements and characteristics gathered by the team through in-person and web analysis. This is followed by the site suitability matrixes used to organize and decipher these characteristics along with comprehensive cost estimates. A cost versus suitability graph is presented to demonstrate the feasibility of each individual design solution. Finally, graphics and explanations of the four living shoreline design combinations are presented.

4.1 General Existing Site Conditions

4.1.1 Site Visit

The first data that the team decided to collect was from the site itself. The team made a trip to the Chelsea Street Bridge on October 3, 2021 to collect measurements of the area under and surrounding the bridge. General observations about the area, such as the soil type, existing structures and layout, tidal water levels, wave height, and adjacent areas, were recorded on a site visit worksheet (Appendix C). A rough site sketch was developed detailing key dimensions and infrastructure (Figure 16). Figures 17 and 18 show the two areas of focus on the site, which are the cobble beach and bank.

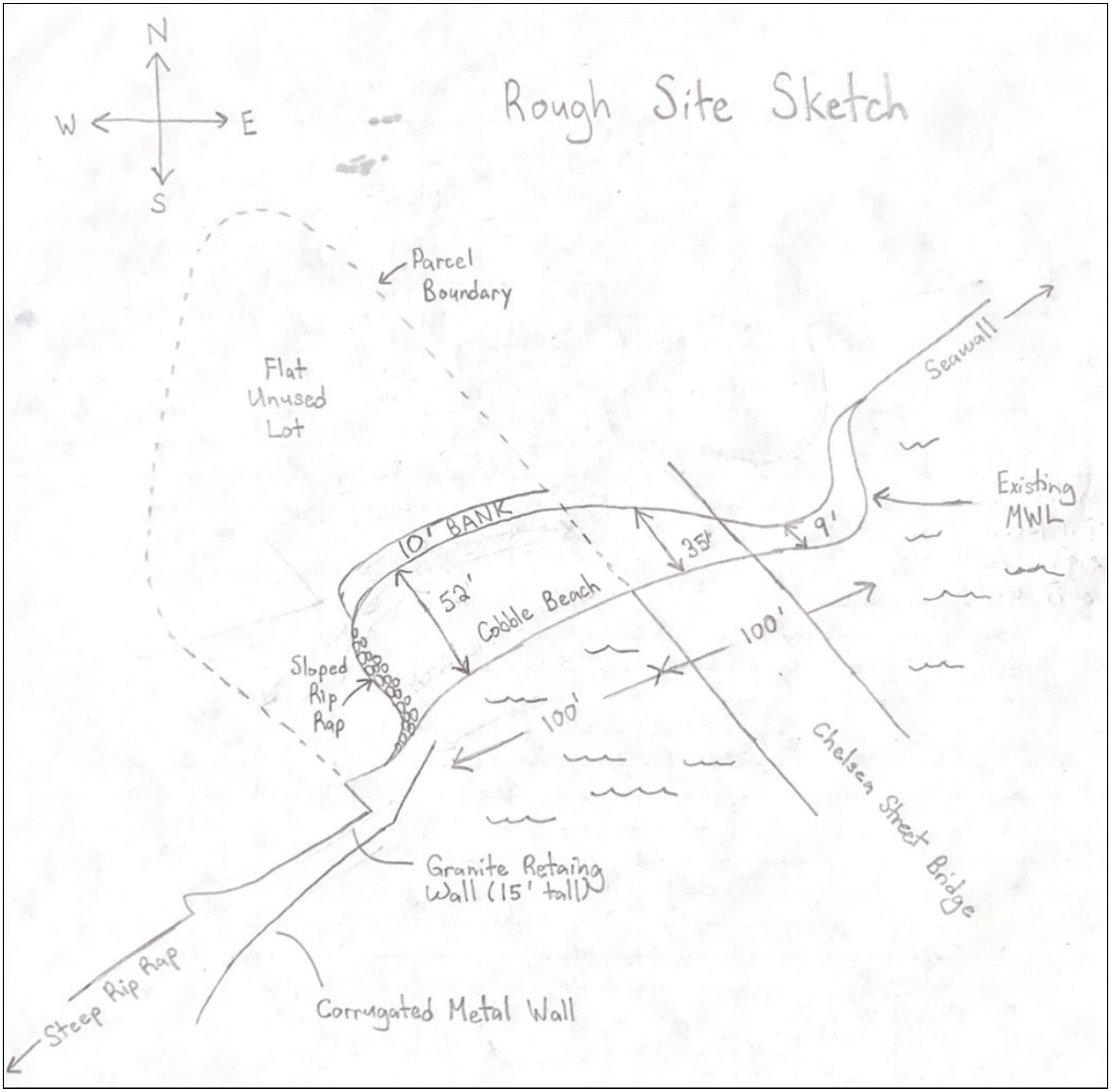


Figure 16: Site Sketch from Information Gathered on 10/03/21 Site Visit.

Figure 17: Bank that Separates the Shoreline Area from the Upland Area.

Figure 18: Cobble Beach (52 Feet Wide by 100 Feet Long).

An initial observation of the area was that all surrounding shorelines, adjacent and opposing, were mostly protected with concrete seawalls (and some rip rap). The bank, which separated the upland zone from the shoreline zone, was measured to be about ten feet in height, with a steep slope composed of a combination of granite blocks, large rocks, driftwood, and vegetation (Figure 17). It was clear that the bank was eroded, especially at the toe. The shoreline zone, or cobble beach, was slightly sloped and had a firm gravel and cobble topsoil which transitioned to sand with increasing depth (Figure 18). The team noted that the upland zone soil was more sandy and rocky with weeds and small brush growing sparsely. The nearshore topography was steep, which aligned with the recent dredging activities in Chelsea Creek (*Maintenance Dredging of the 38-Foot Deep Navigation*).

The main beach received lots of natural sunlight, but the area under the bridge received almost no sunlight, even in the middle of the day. In addition, the areas underneath and east of the bridge had limited distances between mean tide level (MTL) and upland barriers because of the foundation of the bridge and concrete seawalls. Mean tide level is the midpoint of the mean high water and mean low water. The creek current was relatively calm, as it was not a windy day. No boats passed by during the site visit so wakes were not able to be observed. No types of existing aquatic vegetation were identified in the creek. There were a lot of barnacles and mussels on existing structures and some birds in the area, but other than that wildlife was scarce. Seaweed was present on the cobble beach. There was trash and driftwood strewn about the rip rap and the beach, as well as exposed and damaged rebar in the concrete structures.

From the site visit, it was clear that the area had been neglected for some time. This was illustrated by the severely eroded bank toe, driftwood, debris, and degradation of concrete structures. The concrete seawalls surrounding the site were a major concern in terms of high potential for reflected wave energy. The most significant takeaway from the site visit was the lack of existing vegetation and aquatic life.

4.1.2 Site Characterization

After visiting the site, the project focus was narrowed and the parcel in question was characterized in a more sophisticated manner. It was apparent from the site visit that the shoreline west of the Chelsea Street Bridge had the most potential for sustaining a living shoreline. The main reason for this was that underneath and east of the bridge the shoreline widths from MTL to upland barriers were too narrow for soil stabilization and appreciable accretion of sediments to combat sea level rise (SLR). In addition, the area under the bridge is not exposed to sunlight, which the natural aspects of living shorelines need to grow. As a result, the approximately 100-foot long, 52-foot wide cobble beach west of the bridge was selected as the focus area for design. This incidentally coincided with the City of Chelsea's vision for the parcel.

A simple graphic was created to detail the existing natural life on the site (Figure 19). The plant species were identified by uploading pictures of the plants from the site visit into the website Pl@ntNet (*Identify, explore and share your observations of wild plants,* n.d.). While there was limited existing vegetation on-site, the following species were identified: stag-horn sumac at the top edge of the bank, goldenrod upland of the bank, and golden samphire on the bank slope near the Chelsea Street Bridge. Stag-horn sumac was the only vegetation on-site to have appreciable erosion control properties, as sumac species have far-reaching fibrous root systems Stag-horn sumac grows in colonies and spreads aggressively, and is sometimes considered invasive to other existing vegetation. Stag-horn sumac requires annual maintenance to control growth.

Figure 19: Existing Site Ecological Resources.

Site profile sketches were developed using topography data from Meridian Associates' parcel map and from dredging records referenced in the Chelsea Creek Municipal Harbor Plan and DPA Master Plan (Figure 20 and Table 1) (Meridian Associates, 2021; Proposed Chelsea Creek Municipal Harbor Plan and DPA Master Plan, 2021). A copy of the parcel map is included in Appendix D, where it is shown that the shoreline area of this project lies in Parcel 15-4 (15 Eastern Avenue) and a portion of the upland area lies in Parcel 15-5 (29 Eastern Avenue). The upshore bank is approximately eight feet tall, with a slope of 36 degrees from the horizontal. Current mean high water (MHW), mean tide level (MTL), and mean low water (MLW) were obtained from the NOAA and Meridian Associates' parcel map (NOAA, n.d.; Meridian Associates, 2021). The existing tidal lines for the site can be seen in Figure 19. The projected water levels in 2070 were from a bathtub model of 48 inches of sea level rise, which is explained in Section 4.2.1. A sea level rise bathtub model refers to a model in which coastal erosion and hydrodynamic effects are ignored. Thus, the projected water levels in Figure 20 do not account for the potential impacts of erosion, waves, currents, or storm surge on the sea level.

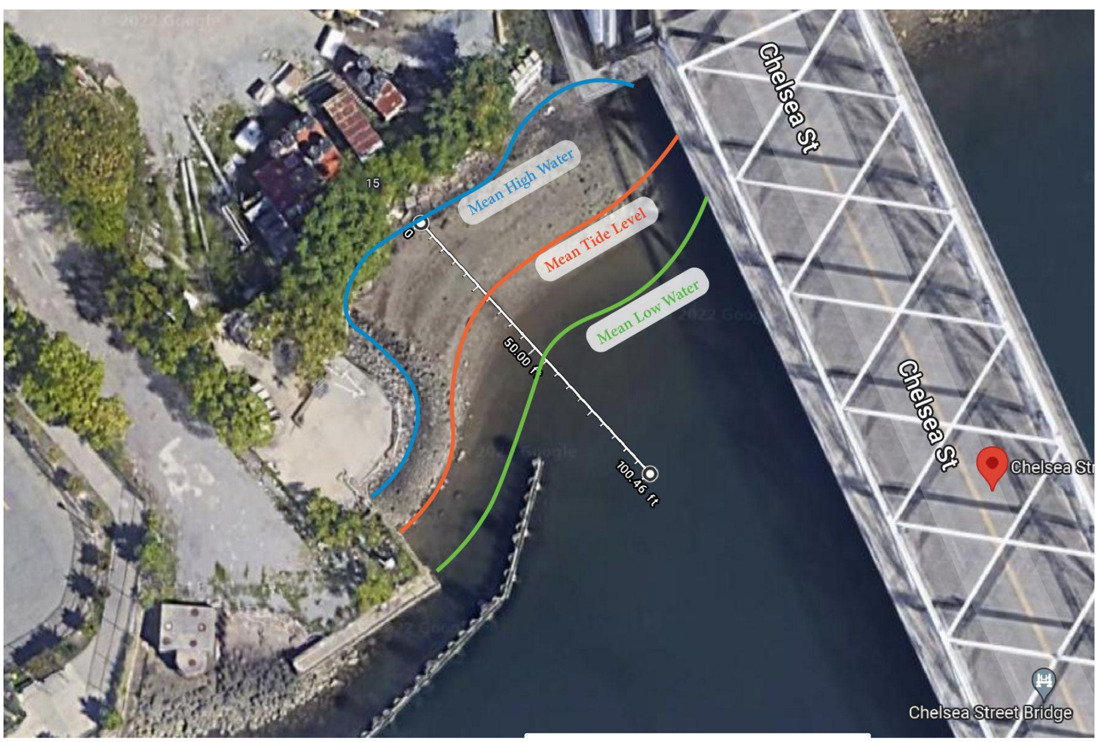


Figure 20. Existing Site Tidal Lines.

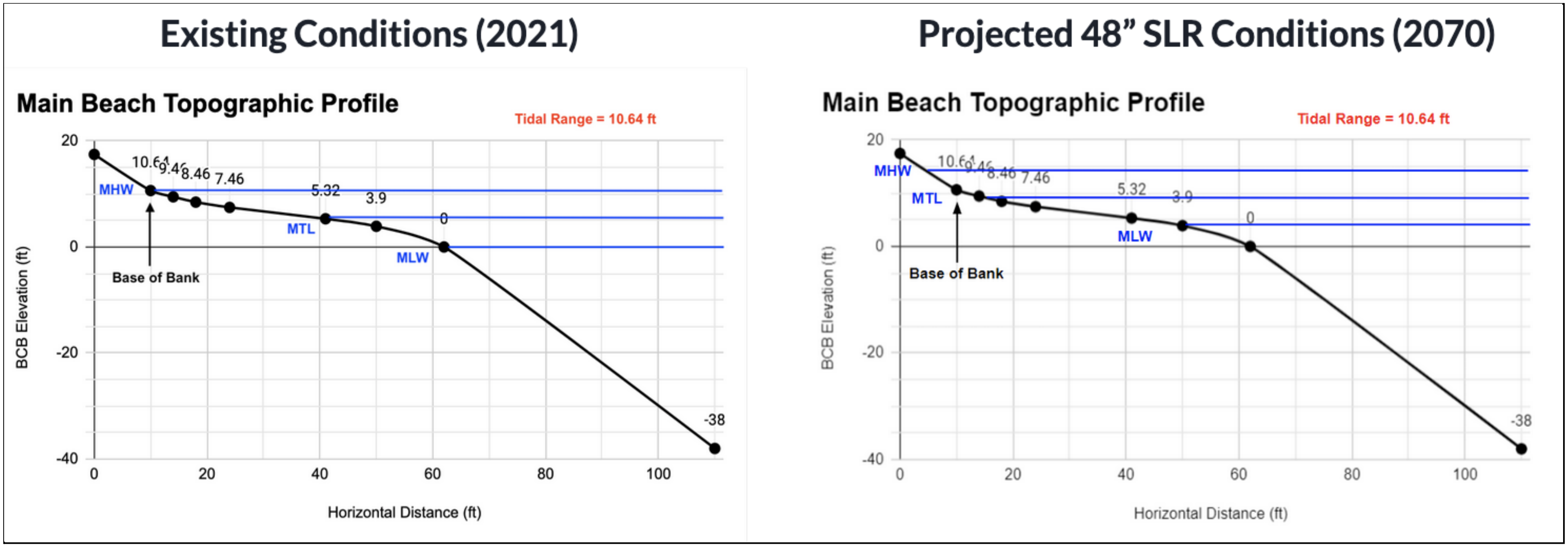


Figure 21: Site Profile with Existing and Projected (2070) Water Level.

Table 1: Summary of Site Profile Key Elevations

Existing Conditions			Projected Conditions (2070)		
Notes	Horizontal Distance from top of Bank (ft)	BCB Elevation (ft)	Notes	Horizontal Distance from top of Bank (ft)	BCB Elevation (ft)
Top of Bank	0	17.46	Top of Bank	0	17.46
Base of Bank and MHW	10	10.64	MHW	5	14.64
MTL	41	5.32	Base of Bank	10	10.64
MLW	62	0.00	MTL	17	9.32
Maximum Creek Depth	110	-38.00	MLW	50	4.00
			Maximum Creek Depth	110	-38.00

A map was created via *ArcGIS* to portray the current flooding impact areas of the project site. In Figure 22, the FEMA FIRMS 100-year flood layer represents the flood event that has a 1% probability of being equaled or exceeded in any given year. The layer represents the base flood elevation (BFE) expected during the 1% storm. The BFE is the 100-yr still water elevation plus the larger of the wave run-up or the wave crest elevation (Miller et al., 2015). Also outlined in the figure is the Chelsea Creek Designated Port Authority (DPA) boundary, which the site is within. The topography upland of the site is relatively flat. Also, there are no additional flood control measures or structures immediately above the site. Thus, once water levels from storm surges eclipse the top of the eight foot bank, there is little resistance to inland water flow. This issue is addressed with future work in Section 6.0 of this report. Impacted infrastructure from the 100-year flood include Marginal Street, Eastern Avenue, TownPlace Suites by Marriott, the Chelsea Screen House, Enterprise Rent-A-Car, Logan Airport parking, and Highland Park. This 100-year flood impact zone will grow with time as sea level rise increases and storm surge events become more frequent.

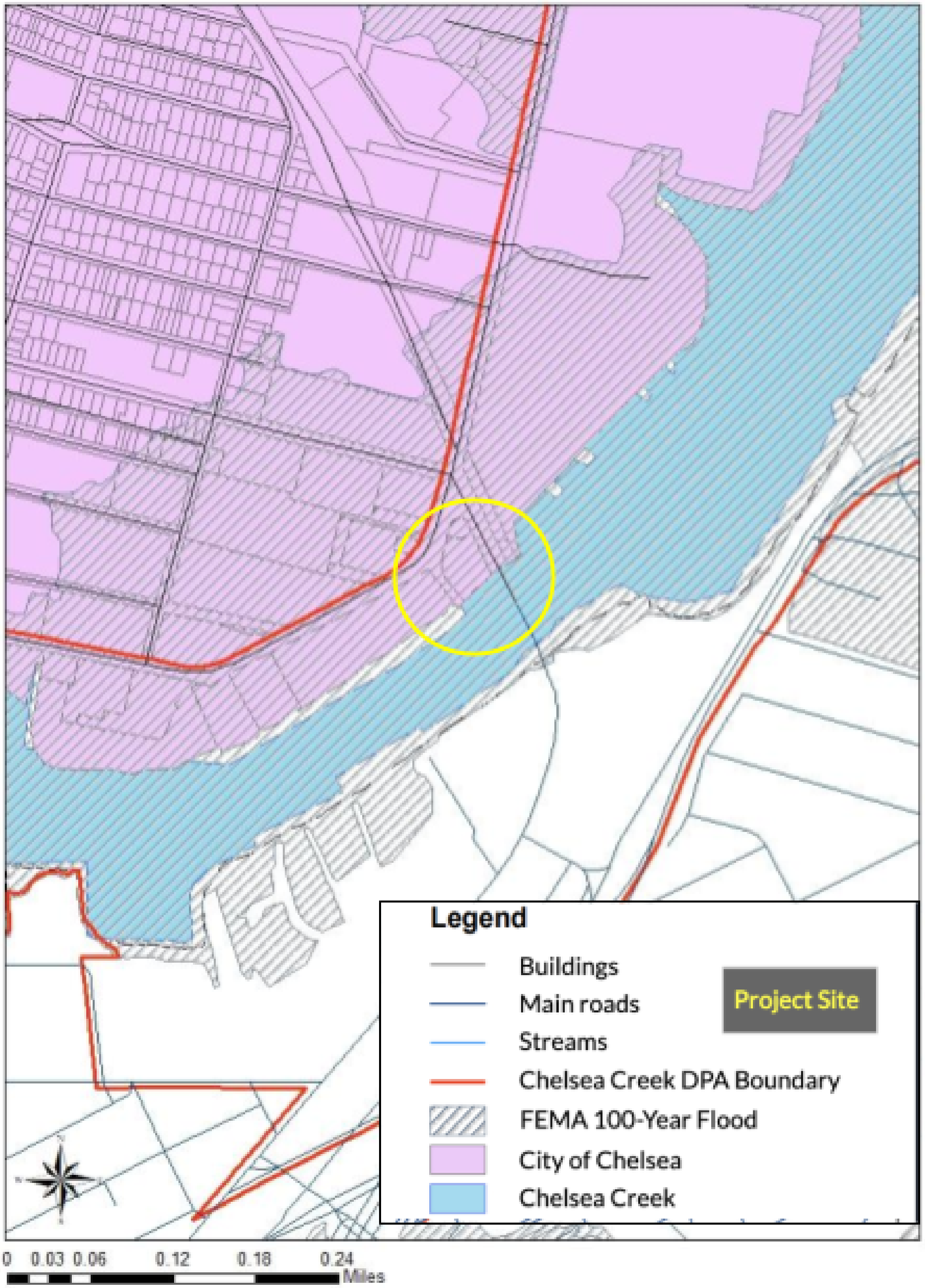


Figure 22: Chelsea Creek 100-year Flood Impact Area at Project Site.

The final step in mapping the project site was to understand the behavior of on-site stormwater. Stormwater inputs from surrounding areas were not a major concern due to barriers blocking water flow surrounding the site and sufficient drainage catch basins on Eastern Avenue and Marginal Street. The direction of stormwater flow from precipitation on the flat and exposed upland portion of the project area was determined using topographic lines from the Meridian Associate parcel map located in Appendix D (Figure 47). Most of the stormwater flows westward, away from the focus of the proposed living shoreline design (the cobble beach). The cobble beach had one critical stormwater input zone between the Chelsea Street Bridge and the stag-horn sumac, on either side of the granite block retaining wall. This is designated by the two southbound arrows on the right side of Figure 23. From the parcel map a stormwater outfall pipe was identified, and it discharges into Chelsea Creek west of the cobble beach. It was not determined whether this outfall pipe was active or inactive.

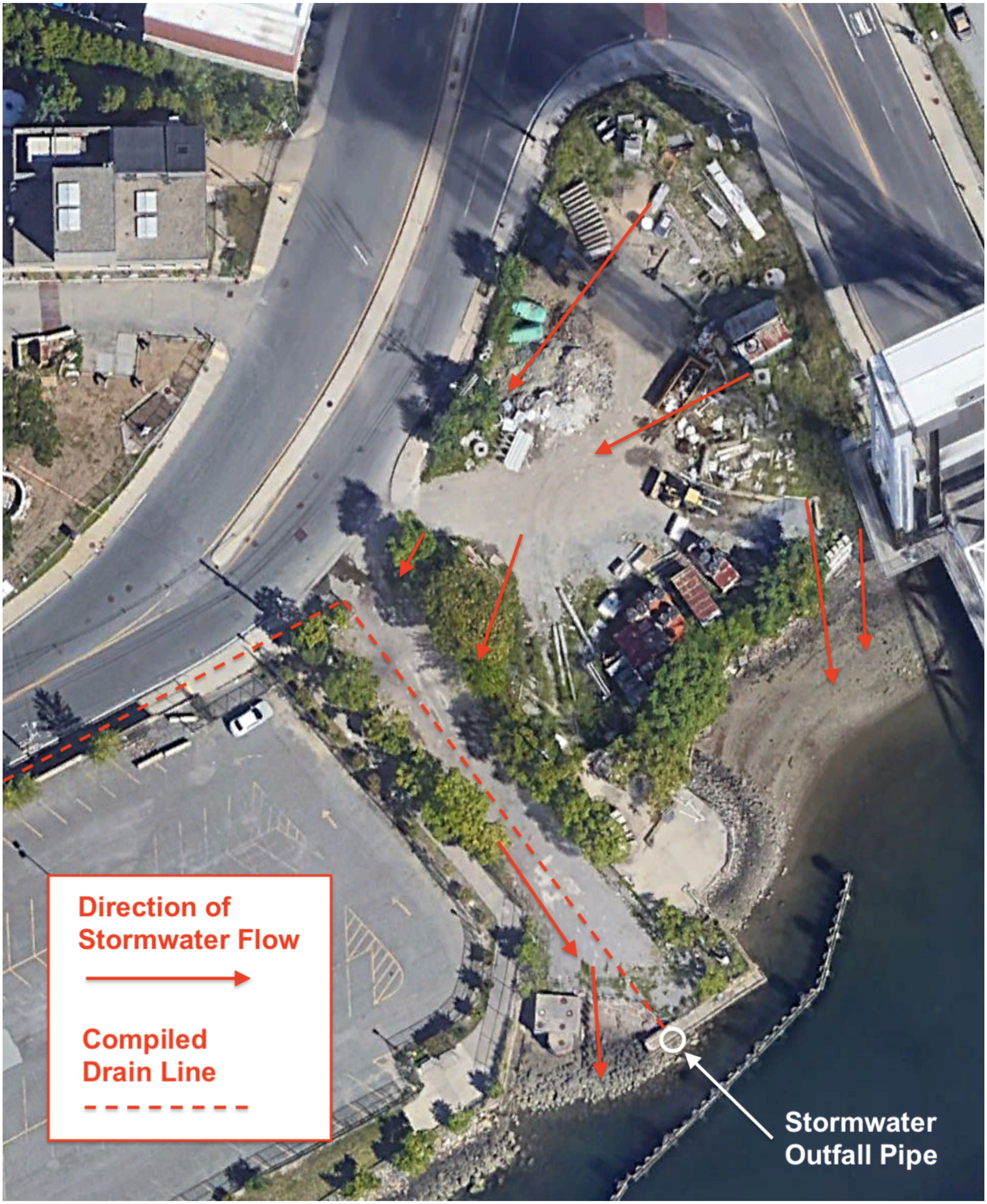


Figure 23: Stormwater Flow Paths from On-Site Precipitation.

4.2 Living Shoreline Site Suitability

4.2.1 Collecting Site Data on Living Shoreline Design Parameters

Once a fundamental understanding of the existing site layout and surrounding land use was established, site data was gathered on the living shoreline design parameters. This data can be seen in Table 2.

Table 2: Site-Specific Living Shoreline Design Parameter Data

	Value	Units	Notes	Sources
System Parameters				
Erosion History	1.5	ft/yr	Assumed value from nearby sites, not a net value (does not include accretion rate)	(A Plan to Increase Coastal Resiliency at Coughlin Park, 2016), (Schwartz, K., & Murray, 2013)
Sea Level Rise	1	in/yr	Based on conservative 48” projection from 2020-2070	(Climate Central, n.d.)
Tidal Range	10.64	ft	Vertical distance between MHW and MLW	(NOAA, n.d.), (Meridian Associates, 2021)
Hydrodynamic Parameters				
Wind Waves	0.5	ft	Average wind wave height	(Climate and Average Weather Year Round in Boston, n.d.), (Windfinder.com, n.d.)
Wakes	1.2	ft	Estimated typical wave height created by barges and tugboats	(rep., 2011)
Currents	0.2	knots	Average creek flow	(US Department of Commerce, NOAA, 2013)
Storm Surge	3	ft	Typical wave heights created by coastal storms	(Designing Coastal Community Infrastructure for Climate Change, 2017)
Terrestrial Parameters				
Upland Slope	73	%	Slope directly above MHW (slope of bank)	(Meridian Associates, 2021)
Shoreline Slope	5.7	%	Slope of the shoreline within the tidal range	(Meridian Associates, 2021)
Width	52	ft	Measured from MLW to toe of bank	(Meridian Associates, 2021)
Nearshore Slope	17.5	%	Slope from MLW to dredged section of creek	(Proposed Chelsea Creek Municipal Harbor Plan and DPA Master Plan, 2021)
Offshore Depth	38	ft	Maximum depth of dredged creek	(Proposed Chelsea Creek Municipal Harbor Plan and DPA Master Plan, 2021)
Ecological Parameters				
Water Quality	Moderate		Graded as an A, but levels of chemicals and stormwater discharge do not aid development of aquatic life	(EPA Mystic River Report Card, 2020), (Carr, 2010)
Soil Type	Udorthents Wet Substratum, Cobble Beach		Shoreline currently has very low ability to retain water and make it sufficiently available for plant use	(United States Department of Agriculture: Natural Resources Conservation Service, 2019), (Brankman & Baise, 2008)
Sunlight Exposure	6	hrs/day	Estimated value from *Google Earth* and average sunlight hours per day	(Sunshine & Daylight Hours in Boston, Massachusetts, USA, 2014)

The sea level rise projection of one inch per year was based on a new study's extreme scenario of forty-eight inches of rise from 2020-2070 (Gaudino et al., 2020). This is an additional twelve inches compared to Climate Ready Boston's predictions in 2016, due to increased emission rates. The NOAA's extreme SLR scenario is about forty inches by 2070 (rep., 2020). The SLR used for design in this project was conservative in order to properly account for the recent significant increase in frequency of coastal flooding events and floods driven by climate-related sea level rise in Chelsea (Figure 24) (Climate Central, n.d.).

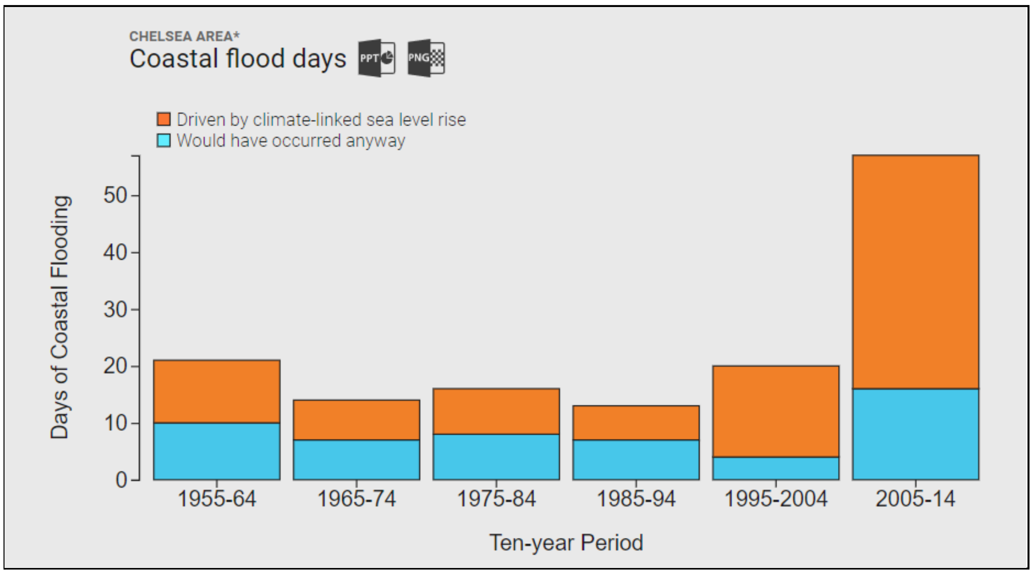


Figure 24: Coastal Flood Days Caused by SLR Per Ten Year Period. (Climate Central, n.d.)

The water quality was assessed as moderate. The 2020 Mystic River Watershed Report Card grades water quality based on the level of bacteria, suspended solids, nutrients, conductivity, dissolved oxygen, water temperature, water color, and odor. These are obtained from samples collected by MRWA volunteers, as well as data collected at numerous locations by the Massachusetts Water Resources Authority (MWRA). The grades are calculated using a three-year rolling average, allowing for a more complete and accurate assessment of recent water quality that addresses weather variability from year to year (EPA Mystic River Report Card, 2020). Although Chelsea Creek's grade for 2020 was an A, there are several factors indicating that the water quality may be lower. First of all, the MWRA sampling site is located at the Condor Street Urban Wild in East Boston. This is slightly closer (about 2,000 feet) to the mouth of the river than the current project site, where there is more circulation and flushing and likely higher water quality (Figure 25). Second, the MWRA samples used for the EPA Report Card do not detect industrial chemical releases or chemicals in stormwater discharged from properties along the creek. This is a major factor, because Chelsea Creek still experiences water quality issues from combined sewer overflows (CSOs) that discharge into the creek when combined sewers overflow from excessive rainfall. Even though there are no active outfalls near the project site, the CSOs most likely have an appreciable impact on the site's water quality (Figure 25). Third, because Chelsea has an overall impervious cover of 75%, the creek receives stormwater inputs containing urban contaminants from runoff in Chelsea, East Boston, Revere, and Everett (*Proposed Chelsea Creek Municipal Harbor Plan and Designated Port Area Master Plan*, 2021). The combination of these factors led to the decision to drop the water quality grade from high to moderate, as summarized in Table 2.

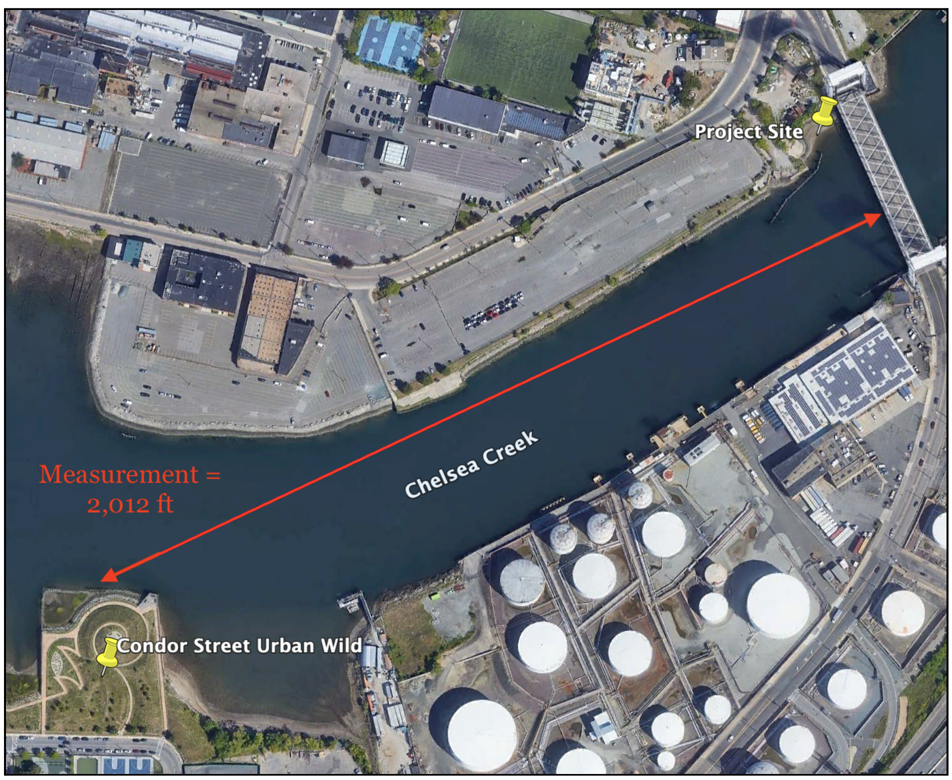


Figure 25: Distance Between MWRA Sampling Site and the Project Site.

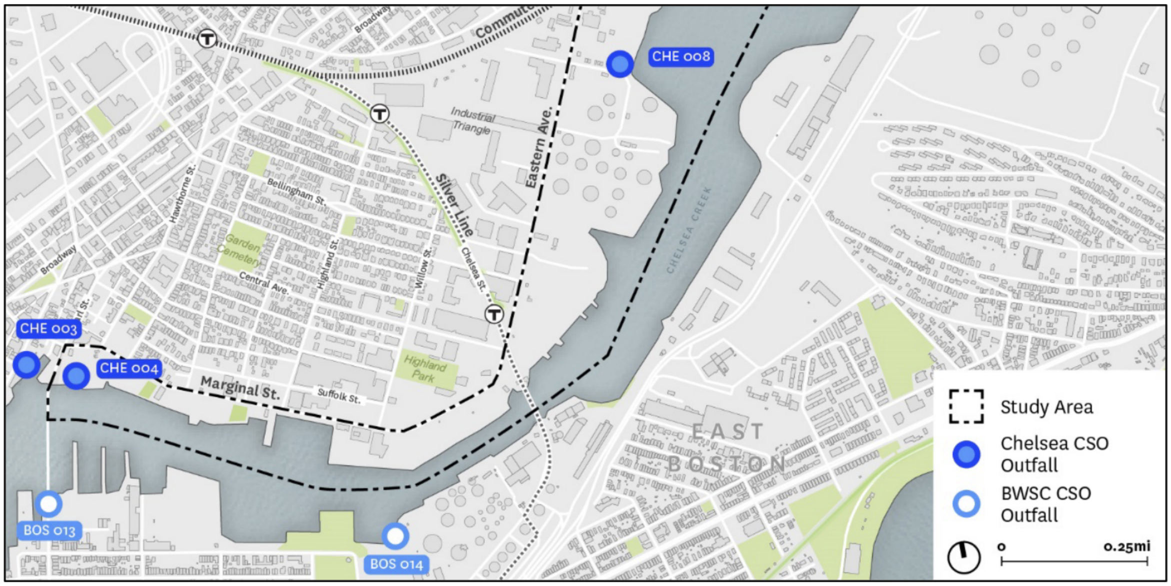


Figure 26: Location of Combined Sewer Overflows (CSOs) along Chelsea Creek. (*Proposed Chelsea Creek Municipal Harbor Plan and Designated Port Area Master Plan*, 2021)

The soil type was classified as "udorthents wet substratum, cobble beach" from the online USDA Web Soil Survey tool (United States Department of Agriculture: Natural Resources Conservation Service, 2019). Udorthents wet substratum designate areas of disturbed soils where the upper soil material has been removed, filled, or graded. The project site is located within an area of artificial fill, as shown by (Figure 27). Soil properties relevant to the evaluation of a soil's capacity to support a living shoreline were gathered from the USDA Web Soil Survey, including pH, erosion factors, organic matter levels, available water capacity, bulk density, frost action, soil susceptibility to compaction, and depth to any restrictive soil layers (United States Department of Agriculture: Natural Resources Conservation Service, 2019). This data was collected for the shoreline area only (the cobble beach), as it is difficult to predict the properties of artificial fill (Table 3). It was concluded from this data that if vegetation were to be used on the existing cobble beach for the living shoreline, supplemental nutritious fill would have to be installed first.

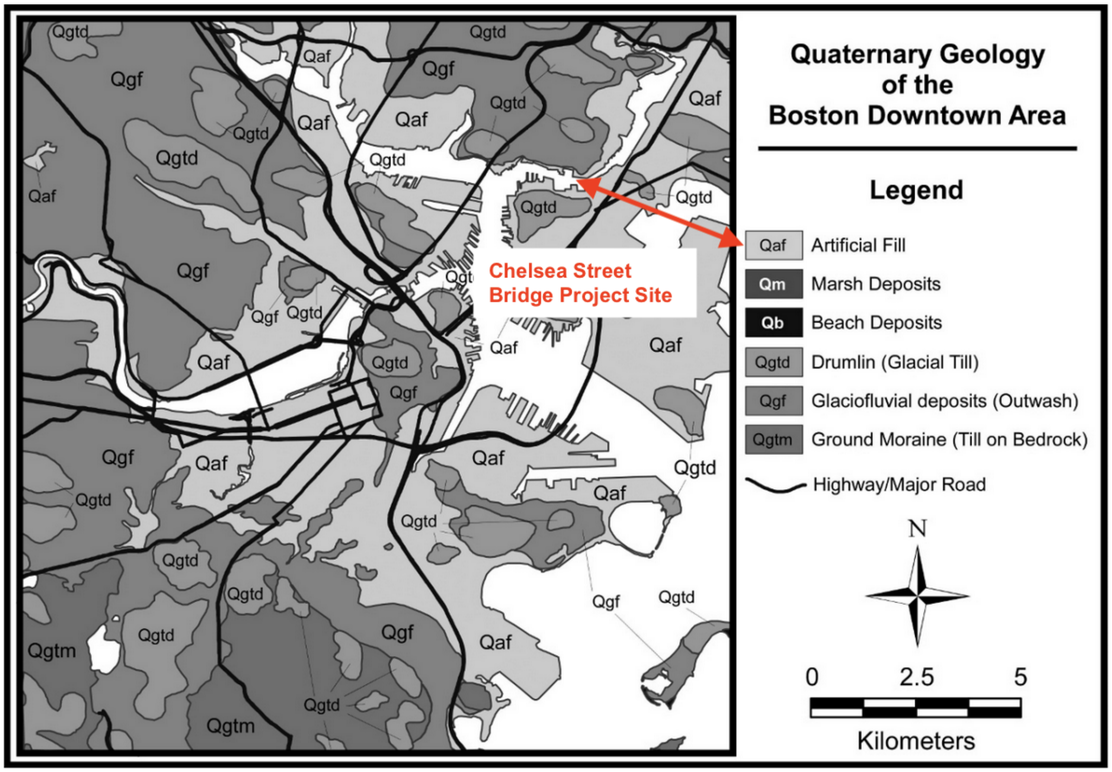


Figure 27: Different Soil Type Areas of the Boston Downtown Area. (Brankman, 2008)

Table 3: USDA Web Soil Survey Soil Properties for Cobble Beaches (United States Department of Agriculture: Natural Resources Conservation Service, 2019)

Soil Property	Rating
Soil Classification	**643, Cobble Beaches**
pH (1 to 1 water)	6.0 (slightly acidic)
Erosion K Factor, whole soil	.02 (ranges from .02-.69, very low susceptibility to erosion)
Wind Erodibility Group	5 (1-8 scale, 1 being the most susceptible to wind erosion)
Available Water Capacity	.01 in/in (very low ability to retain water and make it sufficiently available for plant use)
Organic Matter	.10% (very low, productive agricultural soils have 3-6%)
Liquid Limit	14% (a low value)
Plasticity Index	0%
Bulk Density (⅓ bar)	1.20 g/cm^3 (more than 1.4 g/cm^3 can restrict water storage and root penetration)
Soil Susceptibility to Surface Sealing	Low
Soil Susceptibility to Compaction	Low
Depth to Any Soil Restrictive Layer	> 75 in
Frost Action	Low
Depth to Water Table	6 in
USDA Texture	Extremely gravelly coarse sand
AASHTO Group Classification (Surface)	A-1-a
Unified Soil Classification (Surface)	SP, GP

After site data was collected for the living shoreline design parameters, this knowledge was input into a preliminary living shoreline applicability matrix created by Woods Hole Group (*Living Shorelines in New England: State of the Practice*, 2017). Two iterations of the matrix were completed, with one describing the shoreline area and one describing the properties of the upland bank. The possible broad alternatives output by the matrix for the shoreline area were beach nourishment, marsh creation/enhancement with toe protection, and living breakwater. The possible broad alternatives output by the matrix for the bank area were coastal bank (natural), coastal bank (engineered core), and living breakwater. These matrix suggestions were used as a reference to guide more detailed analyses and decision making.

4.2.2 Living Shoreline Site Suitability Matrix

Once the Chelsea Creek site was fully characterized, the scoring system for the suitability matrix was established. Below are the general scoring range criteria for each design parameter (Table 4) and the weighted significance of each design parameter according to each type of broad coastal stabilization alternative (Table 5). The broad coastal stabilization alternatives considered are a marsh sill, breakwater, revetment, living reef, reef balls, beach nourishment, and bank toe protection. In Table 5, the emboldened design factors are given a multiplier of x2, while the bold and red denotes a critical design factor, which is given a multiplier of x3. The design parameters, scoring range criteria, and weighted scoring system were developed by synthesizing the engineering guidelines from the literature review. The final results of the matrix were presented in Table 6 as the percent site suitability of each broad coastal stabilization alternative.

From Table 6, it is clear that bank toe protection (86% suitability) and marsh sill (80% suitability) obtained the highest scores. According to the matrix, reef balls were the third most suitable option with a site suitability of 74%. The least suitable option was a traditional breakwater (51% suitability), followed by a revetment (59% suitability). In addition to the results from the site suitability matrix, a cost analysis was conducted for each of the seven broad coastal stabilization alternatives (Section 4.3). The combination of the suitability matrix and cost analysis were used to create four living shoreline design combinations. When creating these combinations, the scores of the design parameters from Table 6 were heavily considered to enhance the benefits and mitigate the drawbacks of each broad design alternative. Further detail on these living shoreline design combinations is given in Section 4.5.

Table 4: General Scoring Range Criteria for Site Suitability Matrix

	Criterion				
Parameter	Low/Mild	Moderate	High/Steep		
System Parameters				Notes	
Erosion History	< 2 ft/yr	2-4 ft/yr	> 4 ft/yr	From (Miller et al., 2015)	
Sea Level Rise	< .2 in/yr	.2-.4 in/yr	> .4 in/yr	From (Miller et al., 2015)	
Tidal Range	< 3 ft	3-5 ft	> 5 ft	Estimated from other Research	
Hydrodynamic Parameters					
Wind Waves	< 1 ft	1-3 ft	> 3 ft	From (Miller et al., 2015)	
Wakes	< 1 ft	1-3 ft	> 3 ft	From (Miller et al., 2015)	
Currents	< 1.25 knots	1.25 - 4.75 knots	> 4.75 knots	From (Miller et al., 2015)	
Storm Surge	< 1 ft	1-3 ft	> 3 ft	From (Miller et al., 2015)	
Terrestrial Parameters					
Upland Slope	< 3%	3-10%	> 10%	From (Miller et al., 2015)	
Shoreline Slope	< 7%	7-20%	> 20%	From (Miller et al., 2015)	
Width	< 30 ft	30-60 ft	> 60 ft	From (Miller et al., 2015)	
Nearshore Slope	< 3%	3-10%	> 10%	From (Miller et al., 2015)	
Offshore Depth	< 15 ft	15-40 ft	> 40 ft	Estimated from other Research	
Ecological Parameters					
Water Quality	-	-	-	Estimated from other Research	
Soil Type	-	-	-	Estimated from other Research	
Sunlight Exposure	< 2 hrs/day	2-10 hrs/day	> 10 hrs/day	From (Miller et al., 2015)	

Table 5: Design Parameter Weighted Significance According to the Type of Broad Coastal Stabilization Alternative

		Marsh Sill	Breakwater	Revetment	Living Reef	Reef Balls	Beach Nourishment	Bank Toe Protection
System	Erosion History	**Low-Mod**	**Mod-High**	**Mod-High**	**Low-Mod**	Low-Mod	**Low**	**Mod-High**
	Sea Level Rise	Low-High	Low-Mod	**Low-Mod**	Low-Mod	**Low-Mod**	Low-High	Low-Mod
	Tidal Range	**Low-Mod**	Low-High	Low-High	**Low-Mod**	**Low-Mod**	Low-High	Low-High
Hydrodynamic	Wind Waves	**Low-Mod**	**High**	**Mod-High**	**Low-Mod**	**Low-Mod**	**Low**	**Low-Mod**
	Wakes	**Low**	**High**	**Mod-High**	**Low-Mod**	**Low-Mod**	**Low**	**Low-Mod**
	Currents	Low-Mod	Low-Mod	Low-High	Low-Mod	Low-Mod	Low-Mod	Low-High
	Storm Surge	Low-High	Low-Mod	**Low**	Low-Mod	Low-High	**Low**	**Low-Mod**
Terrestrial	Upland Slope	Mild-Steep	Mild-Steep	**Mod-Steep**	Mild-Steep	Mild-Steep	Low-Mod	**Mod-Steep**
	Shoreline Slope	**Mild-Mod**	**Mild-Steep**	Mild-Steep	**Mild-Mod**	**Mild-Mod**	**Mild-Mod**	Mild-Mod
	Width	**Mod-High**	**High**	Low-High	**Mod-High**	**Mod-High**	High	Mild-Mod
	Nearshore Slope	Mild-Mod	**Mild-Mod**	Mild-Steep	**Mild-Mod**	**Mild-Mod**	**Mild**	Mild-Steep
	Offshore Depth	Shallow-Mod	Mod-Deep	Shallow-Deep	Shallow-Mod	Shallow-Mod	Shallow-Mod	Shallow-Deep
Ecological	Water Quality	**Mod-Good**	Poor-Good	Poor-Good	**Good**	**Mod-Good**	Poor-Good	Poor-Good
	Soil Type	**Organic Sand/Silt**	Any	Any	Any	Any	Any	
	Sunlight Exposure	**Mod-High**	Low-High	Low-High	Mod-High	Low-High	Low-High	Mod-High

Table 6: Site Suitability of Broad Coastal Stabilization Alternatives

		WEIGHTED SCORES						
		Marsh Sill	Breakwater	Revetment	Living Reef	Reef Balls	Beach Nourishment	Bank Toe Protection
System	Erosion History	**6**	**0**	**0**	**6**	3	**6**	**0**
	Sea Level Rise	3	0	**0**	0	0	3	0
	Tidal Range	**0**	3	3	**0**	0	3	3
Hydrodynamic	Wind Waves	**6**	**0**	**0**	**6**	**6**	**6**	**6**
	Wakes	**4**	**0**	**6**	**6**	**6**	**2**	**6**
	Currents	3	3	3	3	3	3	3
	Storm Surge	3	3	0	3	3	**0**	3
Terrestrial	Upland Slope	3	3	**6**	3	3	0	**6**
	Shoreline Slope	**6**	**6**	3	**6**	**6**	**6**	3
	Width	**6**	**2**	3	**6**	**6**	1	3
	Nearshore Slope	0	**0**	3	**0**	**0**	**0**	3
	Offshore Depth	3	3	3	3	3	3	3
Ecological	Water Quality	**6**	3	3	**0**	**6**	3	3
	Soil Type	**2**	3	3	3	3	3	**9**
	Sunlight Exposure	**9**	3	3	3	3	3	3
Total Score		60	32	39	48	51	42	54
Maximum Possible Score		75	63	66	72	69	63	63
% Suitability		80%	51%	59%	67%	74%	67%	86%
Design Area		Shoreline	Nearshore	Upland	Nearshore	Nearshore	Shoreline	Upland

4.3 Cost Analysis

Once the seven design alternatives for the project site had been analyzed in terms of suitability, the cost of each was analyzed. In order to estimate total cost effectively, the total cost of each design alternative was split into material, mobilization, installation, and maintenance. This allowed an upfront cost and long term cost to be estimated. Additionally, some design alternatives were split into different types. For example, a salt marsh sill can either have an oyster sill or a rip rap sill, so both are included in the cost estimate. In Tables 7 to 9, the cost estimates for the design alternatives were split into three different areas of the project: shoreline, upshore, and nearshore.

Table 7: Complete Cost Breakdown for Shoreline Design Solutions

	MARSH SILL			**BEACH NOURISHMENT**
Cost Type	Spartina Alterniflora	Rip Rap Sill	Oyster Shell Sill	Sand, Gravel, and Rock
Material	$1 - $2 /PLANT	$34 - $48 /CY	$40 /CY	$21.50 - $32.00 /TON
Mobilization (of materials and equipment)	$50 - $100 /LF	$10 - $20 /CY	$10 - $20 /CY	$100 /HR (material) $1,000 LS (equip)
Installation (labor and equipment)	$4 /PLANT	$40 - $60 /LF	$40 - $60 /LF	$130 /HR (equip) $75 /HR (labor)
Maintenance (estimates by years)	~$10,000 /YEAR (for first 5 years only)	~$500 /2 YEARS	Full replacement cost every 10 years	$8,500 /2 YEARS
Site Dimensions	100' X 31' = 3100 SF	6' X 100' X 2.5' = 1,500 CF = 55 CY	6' X 1.5' X 100' = 900 CF = 34 CY	52' X 100' X 1' = 3900 CF = 218 TON
Total Cost Breakdown	$24,550 + ~$10,000 /YEAR (for first 5 years only)	$8,080 + ~$500 /2 YEARS	$6,833 + ~$6,833 /10 YEARS	$14,511 + $8,500 /2 YEARS
Notes and Comments	Grows between MTL and MHW, plants spaced at 1.0', self-sustaining 5 years after installation	Maintenance includes additional stones, adding fill at edges from erosion, and removing vegetation, 6-12 inch rip rap assumed	Half life of oysters is 3-10 years, cost is conservative and could be significantly reduced b/c it does not assume use of recycled shells or volunteer work	Assumed 1' of fill added,, fill placed from MLW to toe of bank, needs to be replaced on average every 1-5 years (when > 50% of original fill volume has been lost)

As shown above, oyster shell sill was estimated to have the lowest upfront cost of $6,833 for material, mobilization, and installation. The next lowest cost option upfront was a rip rap sill, costing $8,080 followed by Spartina Alterniflora with an upfront cost of $24,550. The lowest maintenance cost was rip rap, which was estimated to be $500 for every two years. Next was the oyster shell sill which cost $6,833 per every ten years and Spartina Alterniflora at $10,000 per year. Notes are also included for important information regarding cost to each specific design solution.

The complete cost analysis for the upshore design solutions, revetment and bank protection, can be referenced in Table 8. The complete cost analysis for all nearshore design solutions, which are breakwater, living reef, and reef balls, can be seen in Table 9.

Table 8: Complete Cost Breakdown for Upshore Design Solutions

	REVETMENT	BANK PROTECTION			
Cost Type	Rip Rap	Bank Grading	Bank Planting	Sand Tubes	Coir Logs
Material	$82.51 /CY	$21.50 - $32.00 /TON	$1,515	$19 - $30 /LF	$110 EA
Mobilization (of materials and equipment)	$487.39 / EA	$70 - $80 /18.65 TON	~$200 LS	$10 /LF	$480 LS
Installation (labor and equipment)	$190 /HR $137 /LF	~$500 - $600 /DAY	~$2,400 LS	$20 - $35 /LF	$840 LS
Maintenance (estimates by years)	~$1,000 /YEAR	$250 /10 YEARS	$180 LS + $105 /10 YEARS	$6,200 /25 YEARS	~$750 /YEAR (for first 5 years only)
Site Dimensions	3' X 15' X 100' = 4500 CF= 167 CY	100' X 15'	100' X 15'	100 LF	2 Rows along 100 LF
Total Cost Breakdown	$ 15,950.26 + $1000 /YEAR	$1,030 + $250 /10 YEARS	$4,115 + ($180 LS + $105 /10 YEARS)	$6,200 + $6,200 /25 YEARS	$3,520 + ~$750 /YEAR (for first 5 years only)
Notes and Comments	Lifespan is approximately 38 years	Cost is dependent of how the bank is graded, assumed 1 truckload (17 tons) would be enough fill, most fill focused at the toe of bank, maintenance cost is very conservative	$9.50 EA for upland 8"-24" Baccharis Halimifolia shrub (5' spacing), $250 EA for erosion blanket ECC-2B (comes in 4'x225' rolls), $4.00 EA for switchgrass (Panicum Virgatum) with spacing of 2', $0.20 EA for American beachgrass with spacing of 18", installation cost includes 3 instances of fertilizer for beachgrass	Tube has 4.75 ft radius, rarely need to be replaced (every 25 years on average)	Logs are 1' dia x 10' long and weigh 9 pcf (natural net), biodegrade in 5 years, maintenance includes additional planting, anchoring, and new logs

Table 9: Complete Cost Breakdown for Nearshore Design Solutions

	BREAKWATER		LIVING REEF	REEF BALLS
Cost Type	Rip Rap	Oyster Shell	Oyster Shell	Concrete
Material	$34 - $48 /CY	$40 /CY	$40 /CY	$130 EA
Mobilization (of materials and equipment)	$10 - $20 /CY	$10 - $20 /CY	$10 - $20 /CY	$6,565 LS
Installation (labor and equipment)	$40 - $60 /LF	$40 - $60 /LF	$19.21/HR (labor) $547.86 /HR (equip)	$200.00 /HR
Maintenance (estimates by years)	~$2,500 /YEAR	Full replacement cost every 10 years	Full replacement cost every 10 years	~$500 /5 YEARS
Site Dimensions	10' X 100' X 6' = 6000 CF = 223 CY	12' X 100' X 6' = 7200 CF = 267 CY	12' X 100' X 6' = 7200 CF = 267 CY	100 LF
Total Cost Breakdown	$17,488 + ~$2,500 /YEAR	$19,685 + ~$19,685 /10 YEARS	$19,021 + $19,021 /10 YEAR	$14,465 + ~$500 /5 YEARS
Notes and Comments	Costs similar to sill, but larger quantities assumed	Costs similar to sill, but larger quantities assumed		“Bay Ball” design is 3' wide, 2’ tall, and weighs 375-750 lbs, assumed 35 reef balls were used, up to 45 “Bay Balls” can fit on a flatbed truck, structurally can last up to 500 years

4.4 Comparing Cost Versus Suitability

A graphical representation of the relation between the cost and suitability of each specific design type was created to aid decision making. This was developed using the data from both the suitability analysis and cost analysis. The graphical representation (Figure 28) separates the results into four quadrants. The rough average for the long term cost of all design alternatives is about $90,000, which serves as the x-axis on the graph. The upper quadrants of the graph denote the design features that cost over $90,000 dollars. The design alternatives in the lower quadrants cost less than this mean. The right side of the graph shows which of the design features were the most suitable using the scores from the suitability matrix as a percentage, while the left shows the less suitable options.. The average for the suitability of all design alternatives is 70%, which serves as the y-axis on the graph. The four quadrants visually show which features are both low cost and highly suitable, in the bottom right, as well as those that are high cost and not highly suitable, in the upper left. This graphical representation was a useful tool to help determine which design features were the most feasible to incorporate into the potential final designs. This showed that the beach nourishment, oyster shell breakwater, and rip rap breakwater were all high in cost and low in suitability when implemented individually, while sand tubes, coir logs, and reef balls were all low cost and high suitability elements. It also showed which elements were more debatable. For example, rip rap revetment is a low-cost solution but it also has low suitability. Marshes with either a rip rap or oyster sill were higher suitability solutions but cost more. Using this graph, four design solutions were selected that were deemed possible based on the cost versus suitability graph.

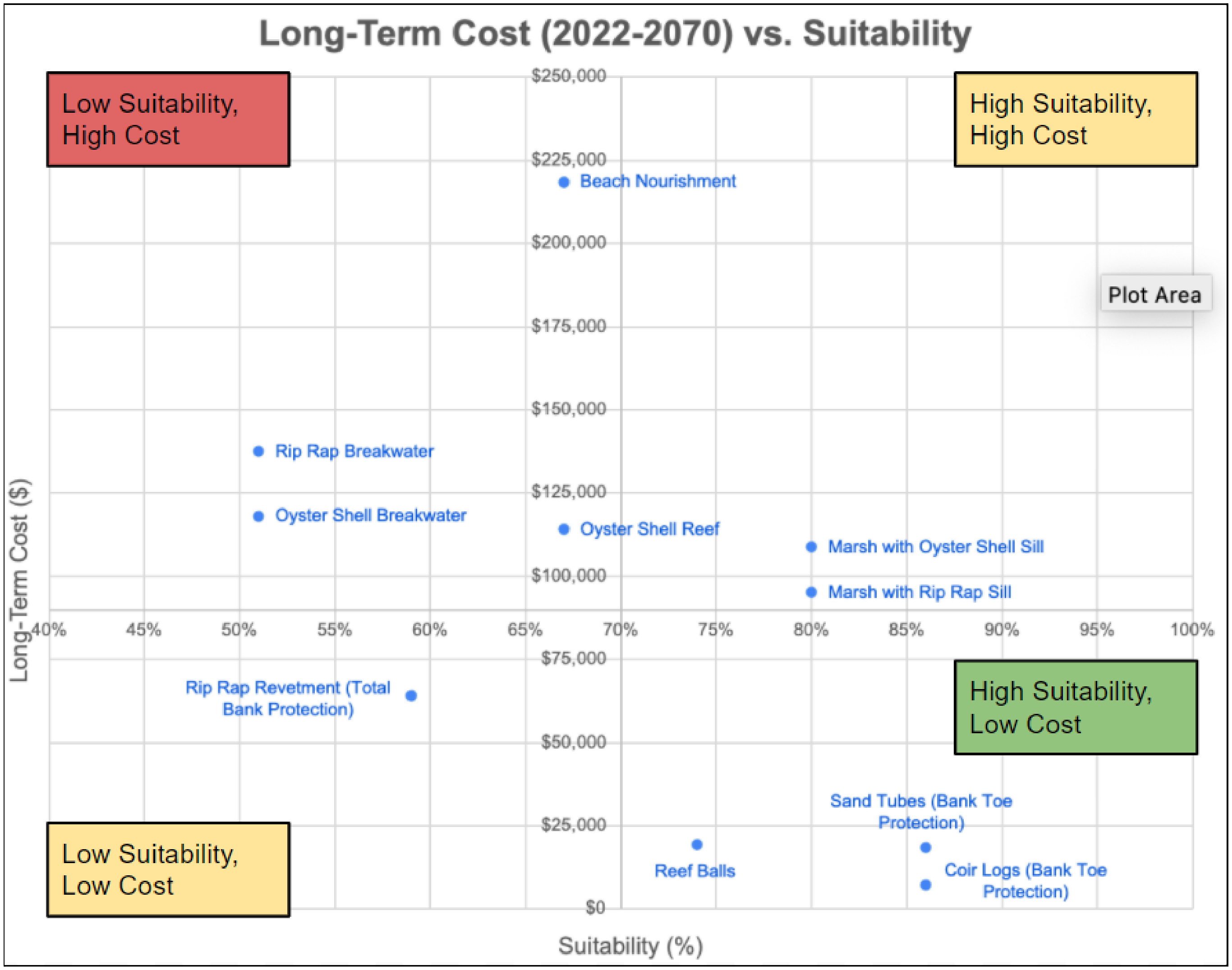


Figure 28: Cost vs. Suitability Graph for Individual Design Alternatives.

4.5 Possible Design Combinations

Four design alternatives were created by combining multiple features together using the information from the cost and suitability analysis in order to make alternatives that would be effective and feasible for the site, both physically and monetarily. There were also some features that were present universally across the design alternatives, such as the planting of shrubs, specifically Baccharis Halimifolia, along the top of the bank to help further strengthen the soil on the bank as well as help with the issue of stormwater runoff. A one-time beach nourishment was also included. This would involve increasing the shoreline six inches in elevation in all designs with a marsh in order to provide more organic soil for the plant roots to establish. The four design alternatives that were debated are listed below. Then, each design is described in detail.

- Design 1 (Marsh with rip rap sill / sand tubes)
- Design 2 (Marsh with rip rap sill / coir logs)
- Design 3 (Reef balls / marsh with oyster sill / coir logs)
- Design 4 (Reef balls / beach nourishment / sand tubes)

Design 1

The first design alternative combines a rip rap marsh sill along the shoreline with sand tubes placed along the bank for toe protection (Figure 29). The design also includes Baccharis Halimifolia shrubs along the ridge of the bank for further strengthening of the bank. The line of rip rap would be used to dissipate the initial wave energy from the channel, followed by the marsh further dissipating that energy as well as rooting the soil to protect it from being washed away. The sand tubes that follow this would be placed along the bank in order to absorb any remaining wave energy and prevent the bank from undercutting and soil loss by holding it in place. The sand tubes would be assisted by the shrubs on the bank which would help to hold the soil in place as well. The total estimated projected cost (through 2070), which includes initial and long-term costs, for this design combination is $129,348 (Table 10).

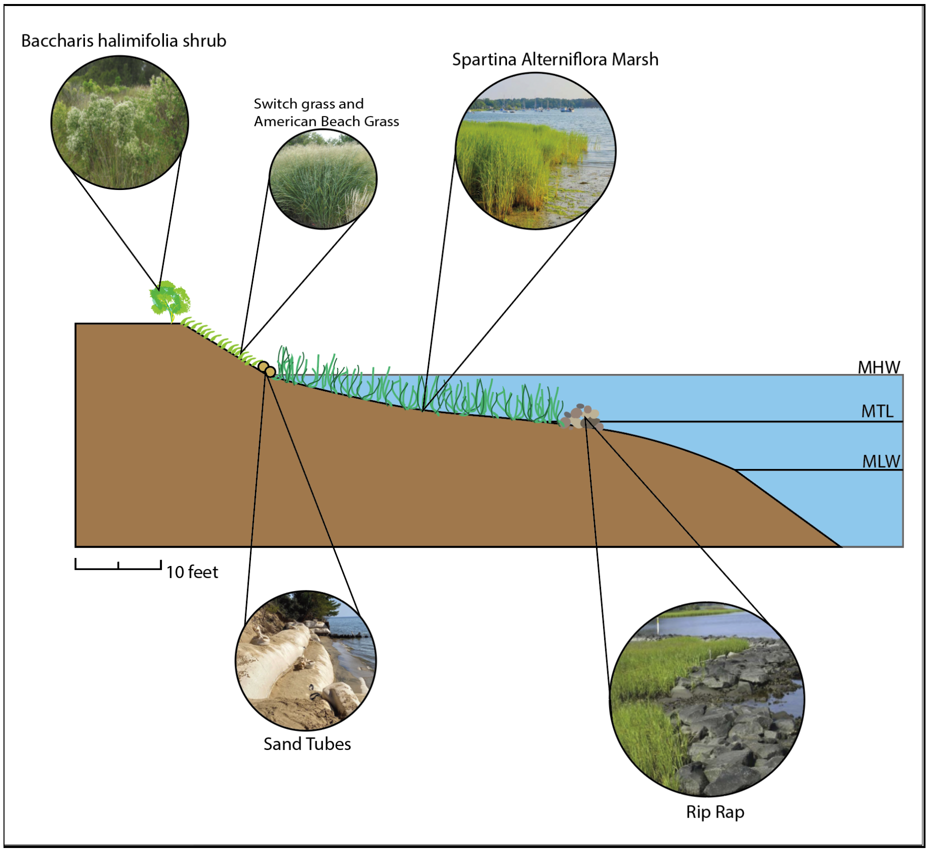


Figure 29: Potential Living Shoreline Design Combination #1.

Table 10: Estimated Cost Breakdown for Potential Living Shoreline Design Combination #1

	Combination 1			
Design Alternative	Beach Nourishment	Marsh	Rip Rap Sill	Sand Tubes
Quantity	109 TON fine-grain (6" before marsh planting, one-time)	3100 Plants	55 CY	100 LF
Location	MLW-Bank Toe	MTL-MHW	Just below MTL	Bank Toe
Spacing	N/A, entire 52' X 100' Shoreline	1' Geogrid	N/A, entire 100' Length	N/A, entire 100' Length
Immediate Cost	$8,518	$24,550	$8,080	$6,200
Total Immediate Cost	$52,493			
Long-Term Cost	$8,518	$74,550	$20,580	$18,600
Total Long-Term Cost	$129,348			

Every Design Combination Includes the Following Costs...		
	Immediate	Long-Term
Bank Grading Costs	$1,030.00	$2,280.00
Bank Planting Costs	$4,115.00	$4,820.00

Design 2

The second design alternative companies a rip rap marsh sill along the shore with coir logs along the bank for the protection (Figure 30). The design also includes Baccharis Halimifolia shrubs planted along the ridge of the bank to further strengthen it. For this design, a line of rip rap would be placed along the shoreline in order to start dissipating some of the wave energy, while the marsh behind it would continue to dissipate this energy as well as further strengthen the soil to avoid being swept offshore. At the toe, coir logs would be placed to absorb any remaining wave energy and stop the bank from being undercut, as well as be used for planting to help lengthen the marsh and strengthen the bank even more. The shrubs along the bank also assist in strengthening and holding the soil at the bank in place. The total estimated projected cost (through 2070), which includes initial and long-term costs, for this design combination is $118,018 (Table 11).

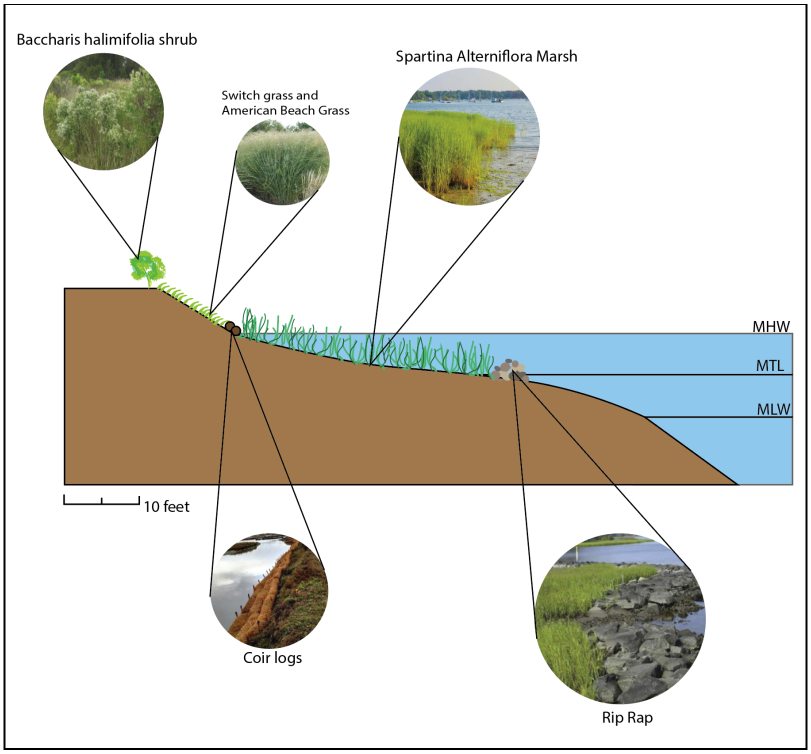


Figure 30: Potential Living Shoreline Design Combination #2.

Table 11: Estimated Cost Breakdown for Potential Living Shoreline Design Combination #2

	Combination 2			
Design Alternative	Beach Nourishment	Marsh	Rip Rap Sill	Coir Logs
Quantity	109 TON fine-grain (6" before marsh planting, one-time)	3100 Plants	55 CY	20 Rolls
Location	MLW-Bank Toe	MTL-MHW	Just below MTL	Bank Toe
Spacing	N/A, entire 52' X 100' Shoreline	1' Geogrid	N/A, entire 100' Length	N/A, 2 rows along entire 100' Length
Immediate Cost	$8,518	$24,550	$8,080	$3,250
Total Immediate Cost	$49,543			
Long-Term Cost	$8,518	$74,550	$20,580	$7,270
Total Long-Term Cost	$118,018			

Every Design Combination Includes the Following Costs...		
	Immediate	Long-Term
Bank Grading Costs	$1,030.00	$2,280.00
Bank Planting Costs	$4,115.00	$4,820.00

Design 3

The third design is a combination of reef balls along the nearshore area, followed by an oyster marsh sill along the rest of the beach, with coir logs along the bank of the shore for toe protection (Figure 31). The design also includes shrubs, more specifically Baccharis Halimifolia, along the bank to further root and strengthen the soil. This design utilized reef balls as the first mechanism to lessen the incoming wave energy that will be frequent from the ships in the channel, which is then followed up by an oyster marsh sill which will further dissipate any remaining wave energy, as well as help to further root the sand along the beach with the marsh. The final element is the coir logs which help to prevent any further undercutting on the bank as well as to provide a base for further planting, which extends the marsh and helps strengthen the soil on the bank even more alongside the shrubs planted on the bank. The total estimated projected cost for this design, including both initial and long term cost through 2070, is $156,251 (Table 12).

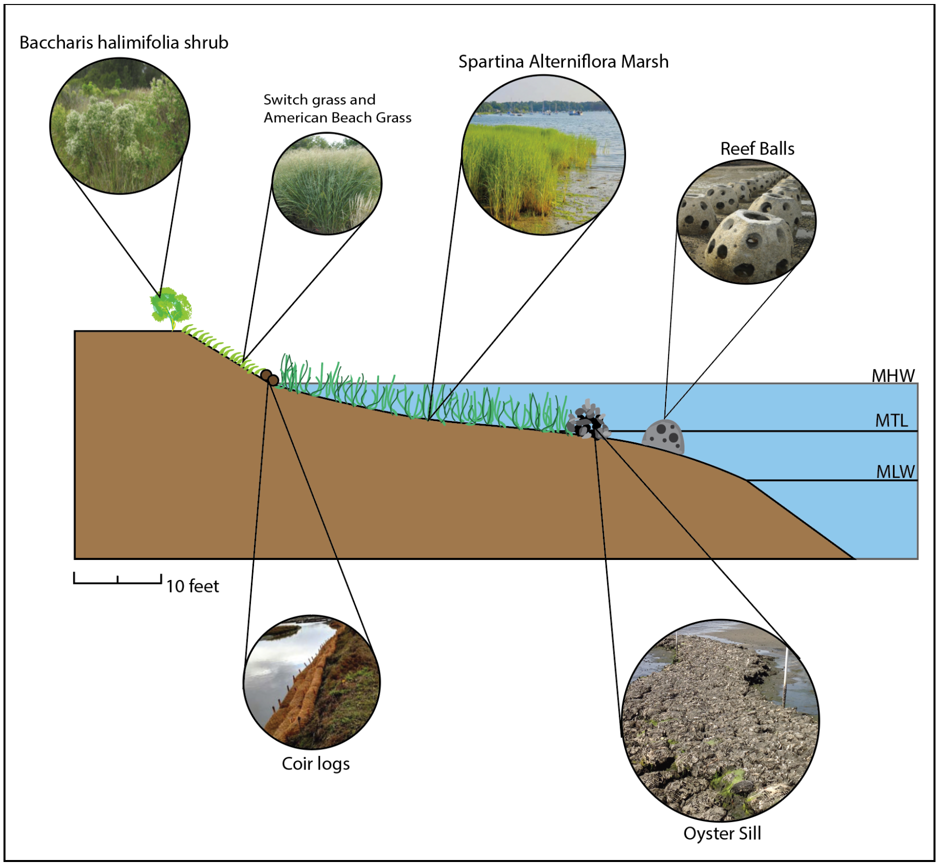


Figure 31: Potential Living Shoreline Design Combination #3.

Table 12: Estimated Cost Breakdown for Potential Living Shoreline Design Combination #3

	Combination 3				
Design Alternative	Reef Balls	Beach Nourishment	Marsh	Oyster Sill	Coir Logs
Quantity	25 Balls	109 TON fine-grain (6" before marsh planting, one-time)	3100 Plants	34 CY	20 Rolls
Location	5' above MLW	MLW-Bank Toe	MTL-MHW	Just below MTL	Bank Toe
Spacing	1 Row @ 1' Spacing	N/A, entire 52' X 100' Shoreline	1' Geogrid	N/A, entire 100' Length	N/A, 2 rows along entire 100' Length
Immediate Cost	$12,815	$8,518	$24,550	$6,833	$3,250
Total Immediate Cost	$61,111				
Long-Term Cost	$17,815	$8,518	$74,550	$40,998	$7,270
Total Long-Term Cost	$156,251				

Every Design Combination Includes the Following Costs...		
	Immediate	Long-Term
Bank Grading Costs	$1,030.00	$2,280.00
Bank Planting Costs	$4,115.00	$4,820.00

Design 4

The fourth design alternative combines reef balls placed in lines along the nearshore with beach nourishment of 1 foot across the shore and sand tubes placed at the bank (Figure 32). The reef balls in the nearshore would serve to dissipate the wave energy while the beach nourishment would make up for any elevation or land lost over time by refilling the area with new sand and cobble for 1 foot of elevation across the shoreline to help maintain its elevation. The beach nourishment would be repeated when necessary to keep the shoreline from falling. Finally, sand tubes would be placed at the bank of the shoreline in order to dissipate any remaining wave energy as well as protect the bank against undercutting. The total estimated projected cost for this design, including both initial and long term cost through 2070, is $267,626 (Table 13).

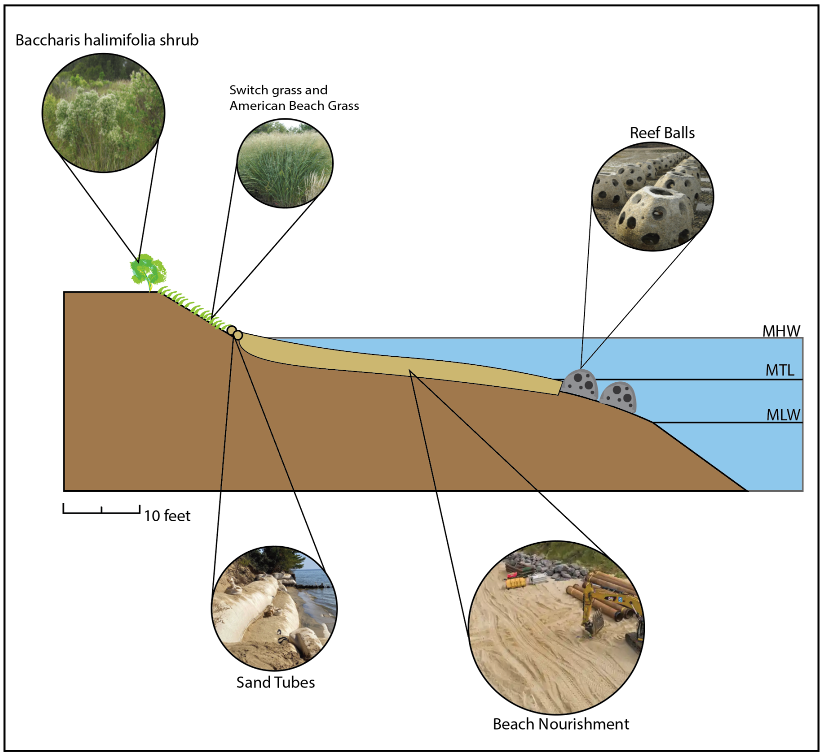


Figure 32: Potential Living Shoreline Design Combination #4.

Table 13: Estimated Cost Breakdown for Potential Living Shoreline Design Combination #4

	Combination 4		
Design Alternative	Reef Balls	Beach Nourishment	Sand Tubes
Quantity	45 Balls	218 TON gravel/cobble (1' fill, repeated)	100 LF
Location	First Row 2.5' above MLW, Second Row 6" above first row	MLW-Bank Toe	Bank Toe
Spacing	2 Staggered Rows @ 1.5' Spacing	N/A, entire 52' X 100' Shoreline	N/A, entire 100' Length
Immediate Cost	$18,415	$14,511	$6,200
Total Immediate Cost	$44,271		
Long-Term Cost	$23,415	$218,511	$18,600
Total Long-Term Cost	$267,626		

Every Design Combination Includes the Following Costs...		
	Immediate	Long-Term
Bank Grading Costs	$1,030.00	$2,280.00
Bank Planting Costs	$4,115.00	$4,820.00

5.0 Recommendations

5.1. Final Design Combination

After comparing the environmental, cost, maintenance, and community impacts of the four living shoreline design alternatives above, a final design was selected. An overview of the decision making process for the final living shoreline design is given in Section 5.1.2.

5.1.1 Presentation of Final Design

The final design combination that was chosen was Design 3. This design was chosen as it is an excellent combination of high suitability for the site, a comparatively lower long-term cost, and a good combination of green design features. This design includes a single row of reef balls along the nearshore area, an oyster sill supporting a salt marsh, coir logs at the toe of the bank, switchgrass and beachgrass on the bank slope, and saltbush on the top of the bank. This design will be placed along the beach directly west of the Chelsea Street Bridge, extending from the edge of the bridge to the rip rap barrier, which is approximately 100 feet west. The design will not extend underneath the bridge, as the lack of sunlight would prove to be a problem for the vegetative elements in our design. The shrubbery in the upland zone will be planted along the top of the 100 foot long bank. A three-dimensional *SolidWorks* shop drawing was created of the proposed living shoreline design, with the MHW and MLW overlayed (Figure 33). In addition, infographics were created for each design element using Adobe Illustrator (Figures 34-41). Another copy of the infographics can be seen in Appendix E. The limitations of these recommendations are explored in the following section.

The successive rows of vegetation in Figure 33 were staggered to maximize erosion control capabilities. This includes both the salt marsh and the bank plants. The gaps in the oyster shell sill seen in Figure 33 were designed to improve faunal access to and from the salt marsh. Salt marsh restoration projects in New England that have overlooked this design consideration have had significantly less faunal presence than projects that included sill gaps.

As seen in Figure 35, anchorage was prescribed for the reef balls. According to the Reef Ball Foundation, reef balls were designed so that they would not require anchors. The weight distribution and hydrodynamics of the modules have been proven to keep them in place through even the worst storms. However, shallow water applications, areas of flat hard bottom, and high energy zones often need to consider anchoring options. This project is in shallow water, has a relatively firm bottom, and medium wave energy. Thus, it was decided that some form of anchorage should be provided (*Reef Ball Brochure & Key Features Page*, n.d.). Based on anchoring guidelines from the Reef Ball Foundation, three to four pieces of battered #5 fiberglass rebar anchors were selected. Fiberglass rebar anchors are inexpensive and resistant to corrosion (*Molds, Suggested Retail Prices & Training/Consulting Services Pricing*, n.d.).

Research of coastal restoration projects revealed that the perennial grasses being used (American Beachgrass and Switchgrass) are capable of growing on relatively steep slopes. For example, a study in Michigan of the long-term health of American Beachgrass found that the beachgrass was tallest on a 43 degree slope. In addition, on the 39 degree slope, the beach grass was the healthiest (Schrotenboer et al., 2015). The existing bank slope on the Chelsea project is approximately 73%, or 36 degrees. Thus, most of the bank grading work for this project will involve adding fill to the severely eroded bank toe. While the slope of the bank could be reduced, it is not necessary to support the components of the living shoreline.

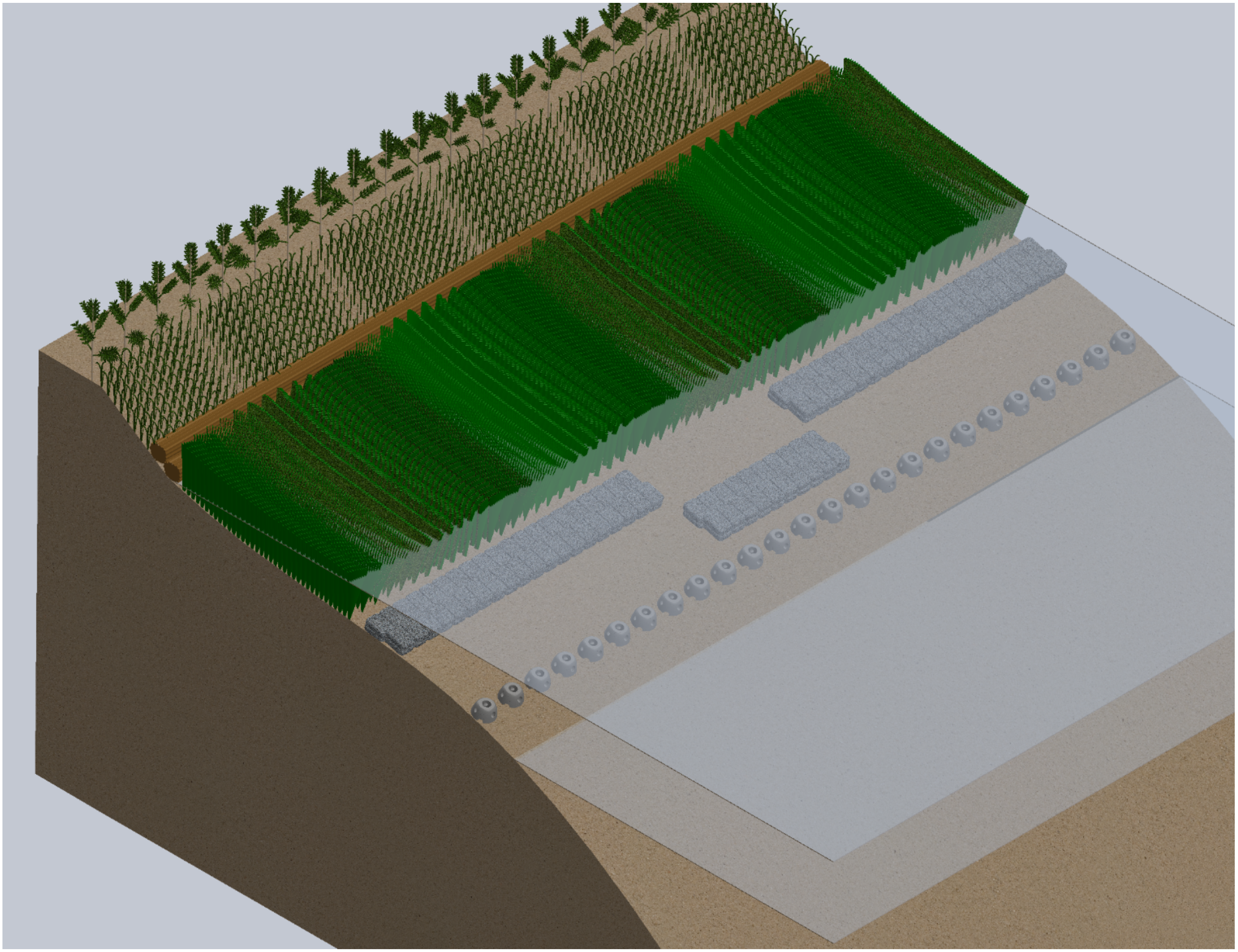


Figure 33. *SolidWorks* Model of Final Living Shoreline Design.

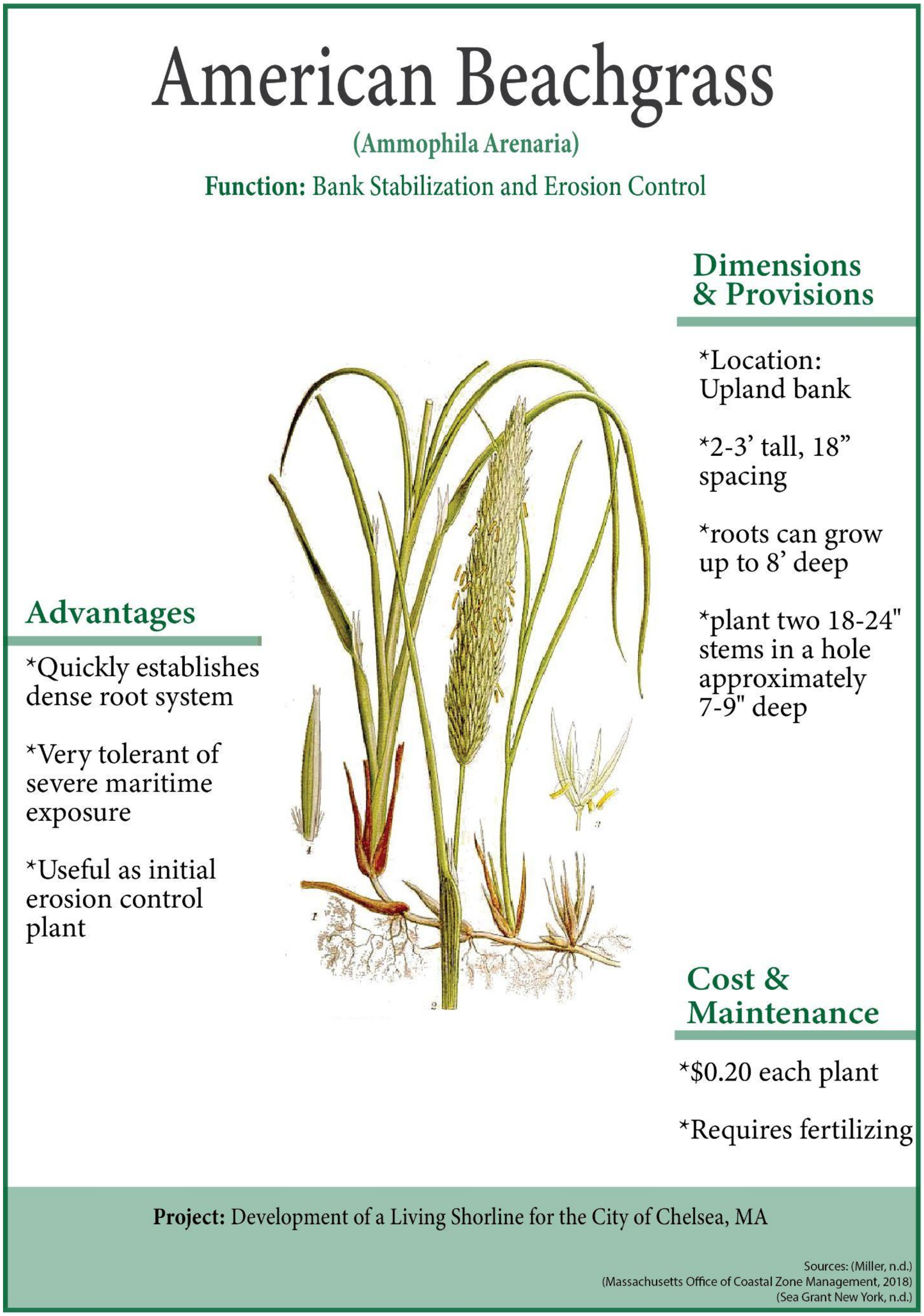


Figure 34: American Beachgrass Infographic.

Reef Balls

(Bay Ball Mold)

Function: Living breakwater

Advantages

* Micro silica concrete has pH similar to seawater and lasts for 500 years

* Easy to deploy

* Great for shallow water

Dimensions & Provisions

* 3 ft base diameter, 2 ft tall

* Weighs about 500 lbs

* 14 interconnecting holes

* Aggregate exposed outside surface texture

* Anchoring provided by 3-4 pieces of battered #5 fiberglass rebar driven into the seabed

Cost & Maintenance

* $130 each ball

* No significant maintenance

Project: Development of a Living Shorline for the City of Chelsea, MA

Sources: (Reef Ball Brochure & Key Features Page, n.d.)
(Molds, Suggested Retail Prices & Training/Consulting Services Pricing, n.d.)

Figure 35: Reef Ball Infographic.

Coir Logs

(Coconut Fiber)

Function: Bank Toe Stabilization and Erosion Control

Advantages

*Protects the toe of the bank

*Helps with erosion control

*Can be planted on

Dimensions & Provisions

*Location: Bank Toe

*1’ dia., 10’ long, 9 pcf (natural net)

*Hardwood stakes staggered 2’ on center on each side

*Rope lashing

* 2 rows across 100 feet, 20 rolls total

Cost & Maintenance

*$110 each roll

*$750 maintenance every year for the first 5 years

Project: Development of a Living Shorline for the City of Chelsea, MA

Sources: (CocoLogix Bank Stabilization Systems, 2020)

Figure 36: Coir Log infographic.

Erosion Control Blanket

(ECC-2B Compressed Coconut Net)

Function: Planting Base and Erosion Control

Dimensions & Provisions	Advantages	Cost & Maintenance
* "ECC-2B"	* Biodegradable	*$250 per 4'x225' blanket
*Uniformly distributed 100% coconut fiber and two organic jute nets securely sewn together with biodegradable thread	*Suitable for slopes 1:1 and medium to high flow channels	*Inspect every 2-3 months for first year for good blanket-soil contact

Project: Development of a Living Shorline for the City of Chelsea, MA

Sources: (East Gate Supply, n.d.)
(Newp, n.d.)

Figure 37: Erosion Control Blanket Infographic.

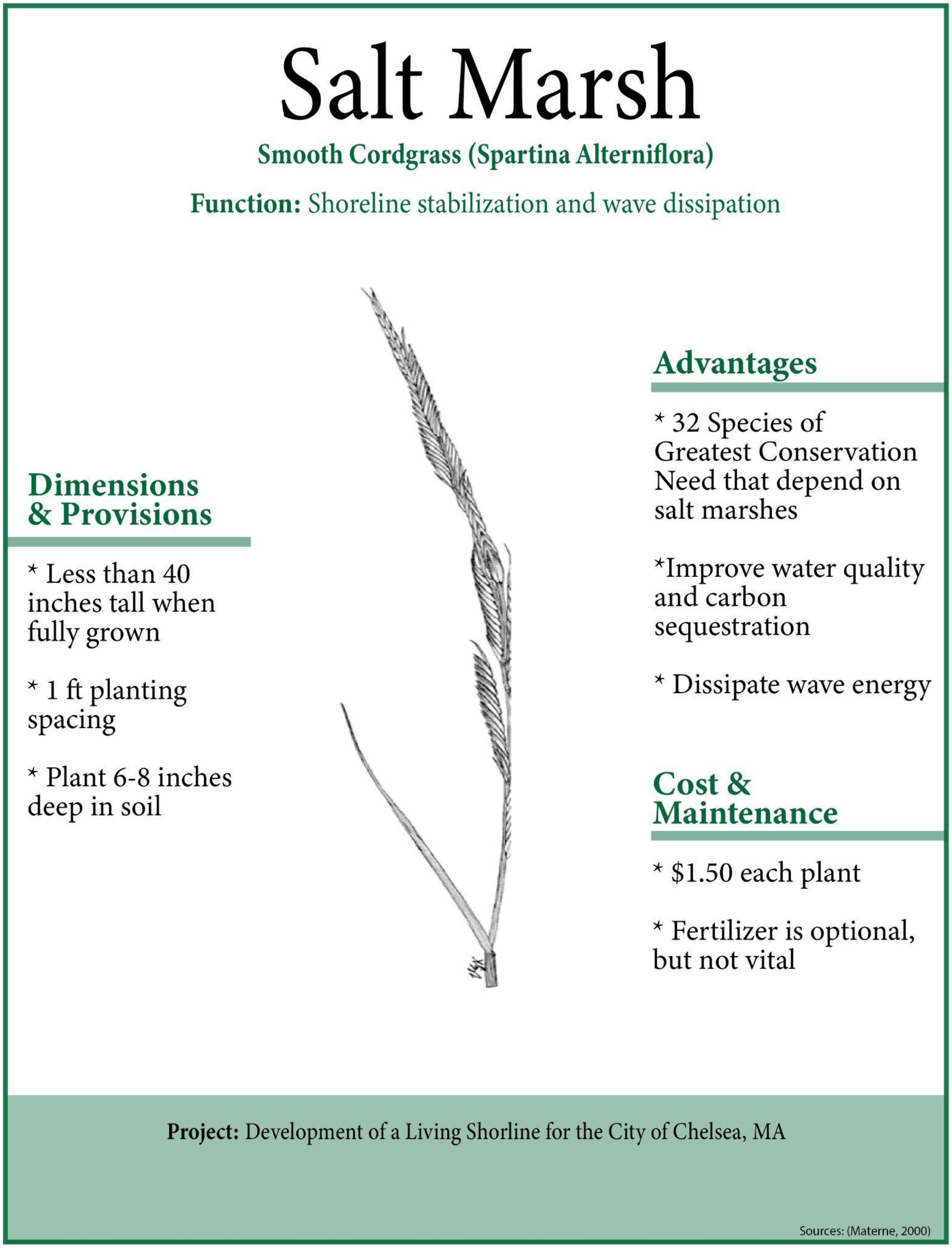


Figure 38. Salt Marsh Infographic.

Oyster Sill

Atlantic Oyster (Crassostrea Virginica)

Function: Living breakwater and marsh toe support

Dimensions & Provisions	Advantages	Cost & Maintenance
* Each bag is 3 ft wide and 1.5 ft tall * 2 bags placed next to each other, 2 bags high	* Increase biodiversity due to richness in calcium carbonate * Improve water quality	* $40 per cubic yard * Inspections to ensure oysters are not buried in the soil

Project: Development of a Living Shorline for the City of Chelsea, MA

Sources: (Milligan et al., 2018)

Figure 39. Oyster Sill Infographic.

Saltbush

(Baccharis halimifolia)

Function: Soil Stabilization and Stormwater Control

Dimensions & Provisions

* 8’-12’ tall

*6’-12’ wide

*5’ spacing

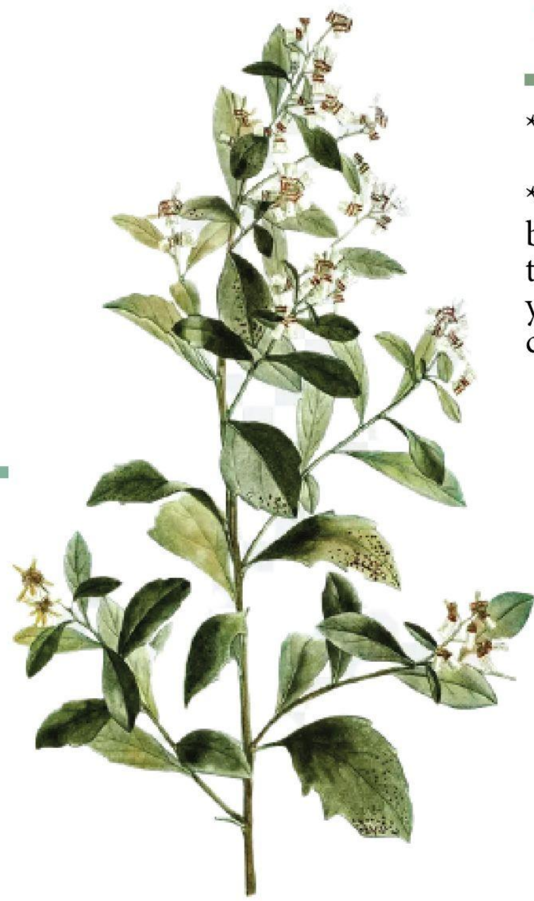
Advantages

*High salinity tolerance

*Native to MA

*Not affected by diseases or pests

*Wide soil type tolerance



Cost & Maintenance

*$9.50 per plant

*Mowing and broadleaf herbicide treatments in 1-3 year intervals to control growth

Project: Development of a Living Shorline for the City of Chelsea, MA

Sources: (Van Deelen & Timothy, 1991)
(New P, n.d.)

Figure 40. Saltbush Infographic.

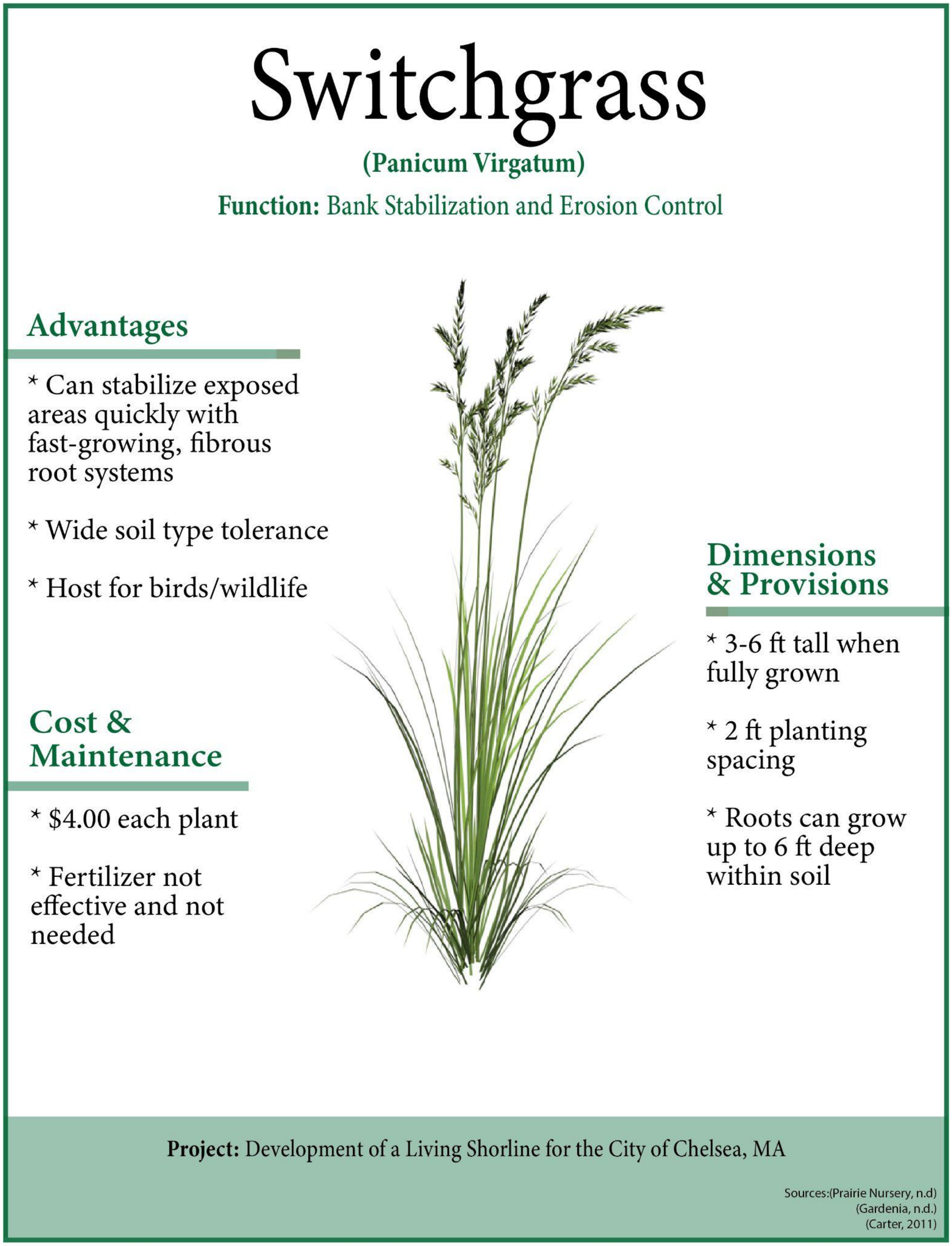


Figure 41: Switchgrass Infographic.

5.1.2 Explanation of Final Design Selection

This design was chosen based on its relative suitability, cost, sustainability, maintenance implications, and community impact.

The decision between stabilizing the cobble beach with a salt marsh or beach nourishment was a fairly straightforward one. The external fill added to a site during beach nourishment usually needs to be replaced every two to five years, depending on the site's rate of erosion. This means that a major construction operation must occur every few years, reducing air quality and resulting in negative impacts on roadways from dump trucks. For the selected site there would be a high risk of the added fill sliding down the steep nearshore slope into Chelsea Creek, perhaps disrupting activities in the federal navigation channel and triggering the intervention of the US Army Corps. On the other hand, salt marshes improve water quality, carbon sequestration, and habitat retention. The key benefit that marshes have over beach nourishment is that their elevation naturally increases with sea level rise and the marsh is typically self-sustaining five years after installation. In addition, there are 32 Species of Greatest Conservation Need that depend on salt marshes (*Profile: Salt Marsh*, n.d.).

An oyster sill was selected over a rip rap sill largely because oysters can increase biodiversity due to their high levels of calcium carbonate and thus improve water quality. Even though rip rap is effective at dissipating wave energy and stabilizing upland soils, it is less aligned with the City of Chelsea's vision for the site, which centers around "living" coastal stabilization measures. According to the literature, installing oyster shells is most successful when healthy oyster larvae are already present, which is not the case for the site according to MassMapper's 2011 "Shellfish Suitability Areas" (*Commonwealth of Massachusetts*, n.d.). However, from a review of research on the improving water quality of Chelsea Creek and the successful oyster installation efforts by the Massachusetts Oyster Project in Boston Harbor, there is confidence that an oyster habitat can be established at the site.

Coir logs were selected over sand tubes because, while sand tubes can last 25 years and are very effective at protecting the toe of the bank from wave induced erosion, they are non-biodegradable, often bury and suffocate native species, and can cause increased erosion at the ends of a project. Coir logs do not suffocate native species, are biodegradable, and can be planted on. Also, the implementation of sand tubes over the past few years in Massachusetts has been met with resistance from local conservation commissions and the Massachusetts Wetland Protection Act (*310 CMR 10.00: Wetlands Protection Act Regulations, n.d.)*.

All of the design elements in this combination fall under the high suitability category with varying costs. The total projected cost (2020-2070) of the selected design combination was $156,251. This cost was slightly higher than design combination 1 ($129,348) and 2 ($118,018), but far less than design combination 4 ($267,626). Due to the emphasis on suitability over cost in this project's design process, the relatively small increase in cost from combinations 1 and 2 to combination 3 was not seen as prohibitive. In fact, it became increasingly apparent that these costs were conservative estimates. Through the all-volunteer nonprofit Massachusetts Oyster Project, recycled oyster shells for the living shoreline can be obtained for free from nearby restaurants, oyster roasts, or seafood companies. The Massachusetts Oyster Project did just this with the summer of 2021 pilot Oyster Shell Recycling Program in Cape Cod, Massachusetts (*Oyster Shell Recycling*, 2021). In addition, a donation for the use of reef balls may be available through the grass-roots initiative No Shoes Reefs and the Reef Ball Foundation. The University of Connecticut received a $10,000 donation in 2021 from these two organizations to install reef balls in the Thames River (*Connecticut College*, 2021).

The combination of the oyster sill and reef balls, dispersing the energy from the waves and wakes in the channel, with the salt marsh, helping to root and strengthen the soil, will both work in tandem to help prevent erosion at the site. The significant level of planting and green solutions incorporated into the design also makes it a more aesthetically and socially pleasing solution as compared to just filling the site with rocks and sand. This design has an appearance as a much more "living" shoreline as opposed to some of the other solutions that, while living shorelines, had a much more gray and unliving appearance. Both the oyster sill and reef balls can help encourage and restore biodiversity. The salt marsh can provide habitats for animals that once called the tidelands of Chelsea Creek their home, including crabs, snails, mussels, oysters, shrimps, turtles, and ducks. The environmental aspects of this design also provides an educational and community focused solution. This design has high potential for being a community resource, as volunteers can help install plants and oysters, locals can come visit the site and enjoy the natural habitat, and schools can schedule educational trips for their students to learn more about environmentally conscious coastal stabilization approaches.

5.2. Implementation Strategy

5.2.1 Construction Plan

A basic construction plan was developed for the final living shoreline design based on research of installation guidelines. The installation order of individual design elements prioritized minimizing negative impacts on existing conditions and protecting new vegetation and life. The chronological order of the major installation steps associated with the living shoreline design are as follows:

1. Installation of reef balls
2. Removal of existing driftwood and large rocks at the toe of the bank
3. Removal of vegetation on the bank
4. Regrading of the bank and installation of coir logs and erosion control blanket
5. Beach nourishment to provide topsoil for salt marsh
6. Installation of oyster sill and salt marsh
7. Planting of new bank vegetation

With proper planning, it may be possible to complete the construction of the living shoreline within one week. This will most likely require the completion of multiple steps in one day. This could most likely be done with Steps 2 and 3, 3 and 4, or 4 and 5. The most comprehensive and time consuming installation steps are Step 1 and Step 6.

Reef balls should be installed first in order to protect the exposed shoreline and upland areas from erosion during construction. In addition, the reef balls will help protect the vulnerable marsh and bank vegetation from wave energy, thus giving them an opportunity to establish their roots. The removal of existing vegetation on the bank is Step 3, while the planting of new bank vegetation is Step 7. These related steps are not adjacent because sufficient shoreward energy dissipation must be provided in order to avoid destruction of newly planted switchgrass and beachgrass. In addition, the removal of bank vegetation and regrading of the bank are relatively early in the construction process because these steps must be done before the beach activities to avoid damage to the salt marsh.

Table 14 gives details on each of the seven major construction steps of the living shoreline, including necessary equipment and labor and construction guidelines. Table 15 provides information on the extent of expected maintenance for each design element of the living shoreline.

Table 14: Details on the Construction Steps of the Proposed Living Shoreline.

Construction Stage	Necessary Equipment and Labor	Construction Guidelines
1. Reef ball installation	Compact excavator and laborers to assist with placement and anchoring (using comprehensive tool kit from supplier)	* Use mats for excavator to prevent ruts and excessive soil compaction * Install fiberglass rebar with sledgehammer
2. Removal of driftwood and large rocks at bank toe	Compact excavator and dump truck	* Use mats for excavator to prevent ruts and excessive soil compaction
3. Removal of bank vegetation	Compact excavator and dump truck	* Use mats for excavator to prevent ruts and excessive soil compaction * Leave some of the sumac root system to maintain some soil stability at top of bank
4. Bank regrading and coir log and erosion control blanket installation	Skid-steer loader and compact excavator for regrading, laborers for coir logs	* Use mats for excavator to prevent ruts and excessive soil compaction * Cover and stabilize soil within 3 days for erosion and stormwater runoff purposes * Ensure erosion control blanket is fully in contact with soil with staples * Bury all upstream and downstream end treatments into the bank for a smooth transition
5. Topsoil beach nourishment	Skid-steer loader and laborers to rake topsoil	* Cover and stabilize soil within 3 days for erosion and stormwater runoff purposes * Minimum of 4 inches of topsoil * Use soil type similar to existing
6. Oyster sill and salt marsh installation	Laborers, as well as hand-held tools for planting	* Install sill before marsh * Oyster sill should be installed before spawning season, which is June-August * Let oyster shells age on land for one year * Provide gaps in sill to support faunal access to shoreline * Salt marsh can be planted between the last frost date and July
7. Planting of new bank vegetation	Laborers, as well as hand-held tools for planting	* Ideally plant saltbush and American beachgrass in early spring (avoid summer plantings or dry soil conditions because these necessitate watering) * Ideally plant switchgrass in late spring to avoid winter storms
Sources	(Clearwater, 2013), (Evans et al., 2011), (Weaver et al., n.d.)	

Table 15: Maintenance Considerations for each Design Element of the Proposed Living Shoreline.

Design Element	Initial Maintenance	Long-Term Maintenance	Sources
Reef Balls	* Possibility for deploying oyster shells in reef balls to foster establishment of aquatic life	---	(*Reef Ball Brochure & Key Features Page,* n.d.)
Oyster Sill	* For first year, check the bottom oyster bags every few months to ensure that they are not buried in the soil	---	(Milligan et al., 2018)
Salt Marsh	* Fertilizer is optional, but not needed * Necessary replantings within first year due to storm surge	* If rapid sea level rise exceeds the marshes sediment accretion rate, may have to move the bank upland to make room for marsh	(Materne, 2000)
Coir Logs	* Additional anchoring with staples	---	(CocoLogix Bank Stabilization Systems, 2020)
Erosion Control Blanket	* Inspect every 2-3 months for first year for good blanket-soil contact	---	(*How and when to use an erosion control blanket,* 2021)
Switchgrass	* Fertilizer is not effective, so don't use * Necessary replantings within first year due to storm surge	* Inspect periodically for disease and overall health	(Carter, 2011)
American Beachgrass	* 3 instances of fertilizer in the first year: 1) 30 days after planting, no earlier than May 1 2) Early summer 3) Late summer * Necessary replantings within first year due to storm surge	---	(Miller, n.d.)
Saltbush	---	* Mowing and broadleaf herbicide treatments in 1-3 year intervals to control growth	(Van Deelen & Timothy, 1991)

The two recommended pieces of heavy equipment to be used on the shoreline area are a compact excavator and a skid-steer loader, as defined in Table 14. This equipment could be rented and kept on-site for the duration of construction necessary, which would be Steps 1 to 5. The heaviest objects that the compact excavator will have to lift will be the existing rocks at the bank toe and the 375 to 750 pound reef balls. The governing constraint on the minimum necessary excavator size is the reach needed to access trucks at the top of the bank from the beach.

Site accessibility issues are important to consider for the heavy equipment expected to be used. For removal and addition of heavy fill and materials, there are two possible access routes for large trucks. One route is entering from Marginal Street and backing down former Eastern Avenue, which is now gravel. At the end of former Eastern Avenue, the trucks can turn onto a concrete pad to position themselves so that the excavator can reach them from the shoreline below. A second route is to enter the currently vacant upland portion of the lot from Marginal Street and position the truck at the top of the project bank area. The advantage of the first route option is that it minimizes soil disturbance and the safety issue associated with large trucks at the top of an unstable bank. However, the strength of the concrete pad and the exact contents underneath it are unknown, so this route might not be feasible. While the second route allows the truck to get much closer to the project area, resulting in more efficient construction, the strength of the soil is also unknown. These site access considerations must be further analyzed before construction.

5.2.2 Integration with City of Chelsea Upland Plans

The City of Chelsea has plans for the unused upland portion of the Chelsea Street Bridge parcel. The City plans to convert the flat area above the bank into a park or similar dynamic open space. The City's vision is to increase public access along the waterfront, which the residents of Chelsea feel is long overdue. The City of Chelsea aims to develop preliminary design drawings for the park at the end of 2023. While the details for the upland portion of the site are still unknown, the City wants to integrate the park design with the living shoreline. In fact, the City predicts that the construction of the park and living shoreline will be simultaneous (Train, 2022).

There is a clear emphasis on increasing public access to the waterfront and creating open spaces for people to exercise in the Greater Boston area, particularly in East Boston. In the

Spring of 2021, the Trustees of Reservations released a draft design of a resilient open space in East Boston called Piers Park III (Figure 42). This project plans to transform an existing abandoned wharf into a space where people can kayak, picnic, or throw a frisbee. The design emphasizes the use of vegetation and sustainable climate resilience via living shoreline components, the main one being several salt marshes (*Piers Park III, n.d.*).

Figure 42: Draft Design of Piers Park III in East Boston. (*Piers Park III, n.d.)*

While the Chelsea Street Bridge project has a much different layout, Piers Park III allows for the potential of waterfront restoration projects in the Boston area to be envisioned. For example, boardwalks could be placed near or within the Chelsea living shoreline with posters detailing the functions and environmental benefits of the design elements. This would provide equitable access to Chelsea Creek and serve as an educational tool to increase coastal resilience awareness in the community. Following the goals within the Proposed Chelsea Creek Municipal Harbor Plan and Designated Port Area Master Plan, the upland space could be filled with outdoor movies and entertainment, food trucks, pop-up markets, or public art. Whatever the intended use, sufficient vegetation or drainage should be provided to prevent excess stormwater runoff into the living shoreline and creek. In addition, the construction of permanent structures near the bank should be avoided to allow for landward migration of the living shoreline as sea levels and the severity of storm surges increase over time. Failing to do so would be detrimental to the salt marsh and bank vegetation, as their position relative to water levels is crucial to their health.

5.3. Permitting Memorandum

A detailed evaluation of the permitting process in the planning stages of a project is vital to ensuring that the project design can be implemented according to existing regulations. This step is particularly useful for this project because the current inclusion of living shorelines in regulations is ambiguous and variable between different agencies, largely due to living shorelines being a relatively new concept. In addition, due to the increased emphasis in the last decade to preserve coastal natural resources and build coastal resilience, coastal projects face numerous permitting barriers. This is especially true for this project, as the site is located within a Designated Port Area (DPA), is on filled tidelands that were previously salt marsh, and is alongside a federal navigation channel.

This section contains details on the state and federal permitting processes that this project would be subject to in the future. The processes are presented in a chronological order and approximate time frames are given. Key steps in the processes are identified and explained.

5.3.1 State Permitting Process

Massachusetts state regulations are written so as to encourage the use of living shorelines over hard coastal stabilization methods. However, Massachusetts does not have a specific definition for a living shoreline, and it is often lumped into other existing regulation terminology.

The key agencies and chronological stages of the Massachusetts state permitting process for the proposed project can be seen in Figure 43. This project is considered a water-dependent use, thus the state permitting process will take anywhere between four and six months. In addition, because this is a municipal project, the Governor of Massachusetts must sign off on the project, which takes about two to three weeks. For municipal projects, all tidelands are considered part of the Commonwealth. Thus, this project will be exempt from state permitting fees and will get an unlimited term license (Taormina, 2022).

Figure 43: Major State Permitting Steps for the Proposed Project, Including the Agencies Involved. (*301 CMR 11.00: MEPA regulations, n.d.; Protecting wetlands in Massachusetts, n.d., Chapter 91, the Massachusetts Public Waterfront Act, n.d.)*

The first step in the state permitting process for this project is review under the Massachusetts Environmental Policy Act (MEPA). The purpose of MEPA is to provide opportunities for public review of the potential environmental impacts of projects and to assist state agencies in using all feasible means to avoid damage to the environment. Since the MEPA process precedes the submittal of permit applications, it provides an important opportunity to identify potential coastal effects at an early stage. It should be noted that approval according to MEPA itself is not a permit. MEPA review is required if a project requires a State Agency Action and meets or exceeds a MEPA review threshold outlined in the Code of Massachusetts Regulations (301 CMR 11.03), which are criteria that the proposed project meets. The Environmental Notification Form (ENF) must be filed with the Massachusetts Secretary. As this proposed project is located within an area of an Environmental Justice Population, public involvement opportunities on the project must be provided for the Environmental Justice Population. The ENF review period lasts for thirty days, within which the Secretary will schedule a site visit and public consultation session with the applicant. Following publication of the ENF in the MEPA *Environmental Monitor*, which provides information on projects under review by the MEPA office, a public comment period will begin and last twenty for days. Some projects require an additional extensive Environmental Impact Report (EIR), but this project does not (*301 CMR 11.00: MEPA regulations*, n.d.).

The second step in the state permitting process for this project is to apply for a permit according to the Wetlands Protection Act (WPA) of the Massachusetts Department of Environmental Protection (MassDEP). The WPA is administered at the local level, in this case the Chelsea Conservation Commission. The act essentially has a “no net loss of wetlands” policy. While the project area used to be a salt marsh wetland, it is not currently classified as a wetland. However, this law also protects 100-year floodplains and riverfront areas specified in the 1996 Massachusetts Rivers Protection Act, both of which apply to this proposed project. The resource areas that the project will alter are, according to Massachusetts General Laws Chapter 131 Section 40: bank, beach, land subject to tidal action, land subject to coastal storm flowage, land subject to flooding, and riverfront area (*310 CMR 10.00: Wetlands Protection*, 2014). Because the project will alter resource areas, an application called a Notice of Intent (NOI) must be filed to the Chelsea Conservation Commission. The NOI requires a plan describing the details of the proposed project, location of wetland resource areas and buffer zones, and measures to be taken to protect them. A NOI is prepared with the assistance of a civil engineer and wetlands consultant. Once the NOI is submitted, the commission will visit the site to verify the resource area boundaries on the property. Then, the commission will host a public hearing. Finally, if approved, the commission will issue a permit, called an Order of Conditions, within twenty-one days of the public hearing (*Protecting wetlands in Massachusetts*, n.d.).

The third step in the state permitting process for this project is to apply for a Chapter 91 license via the Massachusetts Public Waterfront Act. Chapter 91 of the Massachusetts General Laws protects the public's rights in tidelands below the current or historic high water line. A major reason that MassDEP enforces Chapter 91 is to support public and private efforts to revitalize unproductive property along urban waterfronts, in a manner that promotes public use and enjoyment of the water. According to Chapter 91, a living shoreline is classified as a "fill", even though it contains plants (Taormina, 2022). Because this project is working with existing fill and adding fill in the form of a living shoreline, a license is needed, not a permit (*Chapter 91, the Massachusetts Public Waterfront Act*, n.d.). The Chapter 91 licensing application procedure for water-dependent use projects is shown below:

1. Pre-Application Consultation with the Waterways Program staff at MassDEP
2. Chapter 91 Application filed to the MassDEP's Southeast Regional office
3. Formal MassDEP Determination of Water Dependency
4. Notice of license sent to applicant for publication
5. 30-day public comment period
6. File completion review
7. License Issuance
8. Appeal Period
9. Recording of License
10. MassDEP Certificate of Compliance after completion of project

5.3.2 Federal Permitting Process

This living shoreline project requires authorization from the United States Army Corps of Engineers (USACE) because it is located in intertidal waters. The USACE has authority under the Rivers and Harbors Act of 1899 to permit activities that could impede navigation or obstruct navigable waterways, as well as responsibility under the Clean Water Act Section 404 to permit any activities that will impact navigable waters. Permits are issued at the district level, with the district applicable to this project being the USACE New England District (*Softening our Shorelines*, 2020).

In 2017, the USACE issued Nationwide Permit 54 to streamline the permitting process for living shorelines across the United States. However, Massachusetts rejected the use of Nationwide Permit 54 because the permit provisions did not properly align with the environmental conditions of the state (*Softening our Shorelines*, 2020). Although this project does not utilize Nationwide Permit 54, it does require several General Permits (GP) from the USACE.

To qualify for GP authorization, a project must comply with the restrictions of the navigation channel, which in this case is Chelsea Creek. The USACE prohibits any "unreasonable interference" with navigation, which relies on USACE pierhead and bulkhead lines. The bulkhead line defines the limit of solid filling and the pierhead line defines the limit to which open piled structures can be built. As seen in Figure 44, the scope of this project does not interfere with USACE pierhead and bulkhead lines. Some pierhead and bulkhead lines have certain set back requirements. This is often seen in boat marinas. There are no set back requirements for this project (Department of the Army General Permits for the Commonwealth of Massachusetts, 2018).

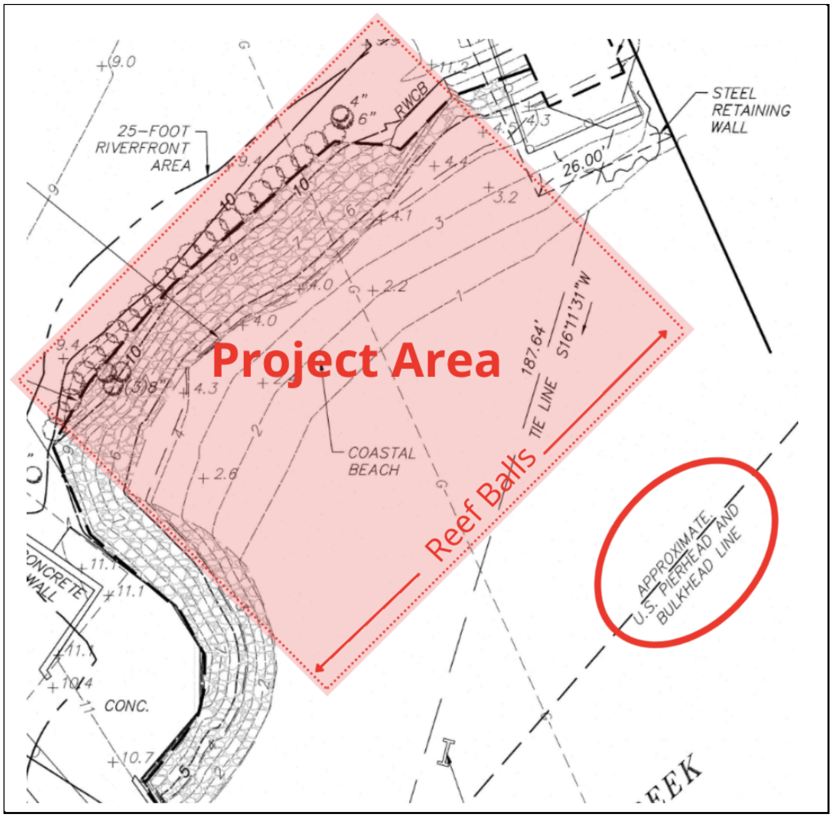


Figure 44: Project Site U.S. Pierhead and Bulkhead Lines (Meridian Associates, 2021).

When applying for project authorization via these General Permits, either a Self-Verification Notification Form (SVNF) or a Preconstruction Notification (PCN) is required depending on activity thresholds. A PCN is more stringent than a SVNF, as a PCN must be submitted to obtain written verification from the Corps before construction can begin. A SVNF is simply a self-verification by the applicant that their project meets the terms of the applicable GPs. The activity and dimensional thresholds of the USACE GPs were reviewed, and the applicable permits to this project were identified, as shown in Table 16.

Table 16: USACE General Permits Required for this Project

General Permit	Permit Applicability	SVNF [1] or PCN [2]?
5 - Dredging, Disposal of Dredged Material, Beach Nourishment, and Rock Removal and Relocation	Covers boulder removal and relocation and beach nourishment from upland sources	PCN [2]
7 - Bank and Shoreline Stabilization	Covers bank and shoreline stabilization activities necessary for erosion control or prevention, such as vegetative stabilization, sills, rip rap, or combinations of techniques (ex. living shorelines)	PCN [2]
23 - Aquatic Habitat Restoration, Establishment and Enhancement Activities	Covers enhancement and establishment of wetlands and riparian areas, provided those activities result in net increases in aquatic resource functions and services	PCN [2]

1: Self-Verification Notification Form

2: Preconstruction Notification

General Permit 5 from the USACE would cover the removal of the large rocks from the toe of the bank and also the one-time beach nourishment to establish the salt marsh. GP 7 would cover the installation of all the living shoreline design elements. GP 23 is focused on projects that plan and design for the establishment of an aquatic habitat that resembles an ecologic reference. The following activities of the proposed project are authorized under GP 23 (Department of the Army General Permits for the Commonwealth of Massachusetts, 2018):

1. "Re-establishment of tidal wetlands in tidal waters where those wetlands previously existed"
2. "Construction of oyster habitat over unvegetated bottom in tidal waters"
3. "Activities needed to reestablish vegetation"

The USACE permitting process can be broken into three major steps: pre-application consultation (for major projects), project review, and decision-making. Seeing that the project area is less than half an acre, pre-application consultation is not necessary for this project. The following list of steps is adapted to this project from the general USACE permitting procedure for General Permits (*U.S. Army Corps of Engineers Permitting Process Information*, n.d.).

1. The applicant submits an application in the form of ENG Form 4345
2. A public notice is issued within 15 days of receipt of a complete application, to solicit comments from the public, adjacent property owners, interested groups and individuals, local agencies, state agencies, and Federal agencies

3. The public notice comment period is 15 to 30 days
4. The Corps may ask the applicant to provide additional information or modify the project according to environmental impacts or resolving public interest concerns
5. A public hearing is held, if necessary
6. The Corps conducts a public interest review evaluation
7. The Corps makes a decision on the permit application and explains its decision within 3 weeks of the last step

It is important to note that the USACE does not charge fees for General Permits, thus this project would be exempt from federal permitting fees (*U.S. Army Corps of Engineers Permitting Process Information*, n.d.).

The Commonwealth of Massachusetts retains the authority to review and approve USACE permits through the Clean Water Act (CWA) Section 401 water quality certification and the Coastal Zone Management Act (CZMA) federal consistency authorities. Section 401 of the CWA gives states an important tool to help protect the water quality of federally regulated waters. However, this is only applicable to projects with point source discharges into the water (ex. pipes). Thus, this project does not require a 401 water quality certification. The CZMA gives states the authority to review projects receiving federal licenses and permits to ensure that they abide by state-defined enforceable coastal policies. To satisfy their permitting requirements, the Massachusetts Office of Coastal Zone Management has collaborated closely with the USACE New England District to develop General Permits. Thus, the USACE GPs are generally consistent with Massachusetts state coastal policies. Therefore, projects that qualify for GPs are not usually subject to additional federal consistency review. It is assumed that this project does not require federal consistency review from the Massachusetts Office of Coastal Zone Management (*Softening our Shorelines*, 2020).

6.0 Limitations and Future Work

The time and resource constraints of this project necessitate an evaluation of the study's limitations and future strategies to address these limitations. When collecting site data, online databases and technical reports were the main sources of information. Table 17 illustrates how for particular design parameters, such as wakes and water quality, more accurate data could be obtained via laboratory testing or on-site measurements. The cost estimates were purely estimates calculated by averaging values from local suppliers or literature on installation and maintenance costs. Obtaining quotes directly from local suppliers and asking individuals about the maintenance of similar shoreline stabilization projects would result in a more accurate cost analysis. These strategies for future work in relation to the cost estimate are in Table 18. The study of sustainability implications was limited due to the lack of literature on the long-term impacts of living shorelines. A major sustainability limitation was due to the use of a bathtub model for sea level rise and associated flooding impacts. In the future, hydrodynamic modeling would allow for the investigation of potential impacts of the living shoreline on adjoining areas, such as the scour potential along the abutments of the Chelsea Street Bridge. Table 19 details how utilizing the expertise of professionals and consultants would greatly expand upon the sustainability discussion in this report.

Table 17: Data Collection Limitations

Site Parameter	Limitation	Future Strategies to Address the Limitation
Erosion History	Data was obtained through research of erosion rates at sites in the area, which may not reflect this site's true conditions.	To perform a more intensive analysis, interviews with public works directors, adjacent landowners, and environmental commission members can be conducted.
Sea Level Rise Projections	A bathtub model was used to predict the sea level in 2070, which does not account for hydrodynamic influence. In addition, a very conservative SLR estimate of 48 inches was assumed.	A more thorough analysis can be performed using the US Army Corps of Engineers approach outlined in a guidance document for calculating sea level impacts.
Wind Waves	A desktop analysis using the NOAA was performed in order to obtain wind wave ranges for the general area, however, specific measurements were not taken directly from the site which can skew any assumptions made.	Wind wave measurements can be carried out at the site using multiple measurement instruments such as a pressure gauge, accelerometer buoy, acoustic wave gauge, wave wire or lidar and radar. Additionally, a wave model can be created to provide a detailed analysis of wave patterns at the site.
Wakes	Wake waves were quantified through research of typical wake heights for certain ships and speeds. In addition, the width of the creek and the seawalls on the opposite shoreline were taken into account. This was a generalized method that did not produce the most accurate results.	A visual on-site method can be used to measure wake wave height. This involves using a graduated rod to visually record the water surface oscillations. Video recordings can be made to check initial observations and to obtain a better estimate of the wake period. The measurements should be repeated several times.
Water Quality	A web analysis was conducted in order to predict the water quality in the surrounding area and assumptions were made about the specific site. The obtained information was limited to ranges rather than exact quality measurements.	A water sample can be collected in order to perform a full analysis on its quality. The analysis will measure the water's dissolved oxygen levels, water temperature, salinity, and turbidity.
Soil Type	The USGS Web Soil Survey tool was used to characterize the soil. Values for various physical and chemical properties were obtained. This data was generalized for each broad soil type, and no data was available for the bank and upland area.	Samples can be taken along the shoreline, upland, and offshore. If fill is to be imported, samples should be taken to ensure compatibility of the fill material with the native sediments. Lab tests on the soil could include a moisture content test, direct shear test, Atterberg Limits test, etc.

Table 18: Cost Analysis Limitations

Design Parameter	**Limitation**	**Future Strategies to Address the Limitation**
Materials	Material costs can fluctuate based on lead times, supply and demand, inflation, and different suppliers. The material costs used in this report were estimated from local suppliers and literature on coastal stabilization projects.	Quotes from multiple local suppliers should be obtained. Average material costs can be evaluated on an annual basis to gain an accurate representation of a material's market value.
Installation	The installation costs calculated in this project were based on an 8 hour work day and assumed laborer and operator hourly wages. These wages were assumed from similar construction industry jobs. In addition, the number of laborers needed was assumed. Some design elements (ex. oyster sill) could be installed by volunteers, thus reducing the overall installation cost.	Several construction companies should be contacted to devise a plan for the expected duration of work, number of workers required for installation, and hourly laborer wages. In addition, organizations like the Massachusetts Oyster Project should be contacted to determine if the material can be installed by volunteers.
Maintenance	Maintenance was especially difficult to estimate due to uncertainty towards the resilience of certain design elements over time. This uncertainty stemmed from living shorelines being a relatively new concept with minimal concrete long-term maintenance data. In addition, the cost of materials and labor change over time.	As the use of living shorelines becomes more common and data is collected on their long-term resilience, maintenance costs can be more accurately calculated. An inflation factor should be used in long-term projections.

Table 19: Sustainability Considerations Limitations

Topic of Concern	Limitation	Future Strategies to Address the Limitation
Flooding and Storm Surge	There is little focus on storm surge and significant flooding for living shorelines because most of the approaches are low lying and will be overtopped during extreme storms. In addition, because living shorelines are a relatively new design concept, quantitative data for the storm resilience of different types of living shorelines is not available and was not analyzed.	As the use of living shorelines becomes more common and data is collected on flooding and storm surge resilience, these parameters can be more accurately measured. Maximum storm thresholds suitable for the living shoreline components should be identified.
Impacts on the Surrounding Environment	Potential living shoreline impacts on the surrounding land were not analyzed due to time constraints. End effects of the living shoreline on adjacent lands were limited by tying into adjacent shore protection works and by gradually transitioning back to a natural coastline.	While living shoreline projects tend to have smaller end effects as compared to traditional shoreline stabilization projects, they must still be analyzed. For example, hydrodynamic models would allow for scouring potential around the Chelsea Street Bridge abutments to be analyzed. In addition, potential impacts of adjacent engineering projects along Chelsea Creek on the living shoreline should be analyzed.
Stormwater Impacts	Minimal potential stormwater runoff paths were identified by analyzing the topography of the site. However, the runoff was not quantified (velocity and volume), thus impacts were not determined.	The volume of runoff can be obtained through simple engineering calculations. Stormwater velocity may have to be determined via on-site measurement. To determine the impact of the stormwater on the living shoreline, a sample of the stormwater should be tested for contaminants.
Community Impacts	This report identified some opportunities for community involvement and generally noted positive and negative impacts on the area. However, comprehensive analyses were not conducted for the community impacts.	A Community Impact Assessment should be conducted by the project planner. Public involvement in the early stages of the planning process is vital.
Park Implementation	The City of Chelsea does not yet have design ideas for the upland portion of the site. Thus, specific means to integrate the park with the living shoreline were not specified in this project.	An environmental consultant should be involved in the design of the park area to ensure that short and long-term negative impacts on the living shoreline are minimized (ex. avoid permanent structures at the top of the bank, provide sufficient vegetation for stormwater management).

7.0 Conclusion

The particular prevalence of sea level rise in New England increases the risk of flooding in coastal communities like Chelsea, MA. A large portion of the Chelsea population is not only at an elevated risk of flooding, but they also do not have the resources necessary to recover from the effects of flooding. In addition, the industrial operations in the City subject the population to poor environmental conditions, and the community has long asked for more equitable access to Chelsea Creek. Thus, the need for a sustainable coastal stabilization system that encourages public access to the shoreline is evident. This project's living shoreline design took into accounts all of these needs.

Rigorous background research was conducted in order to gain a thorough understanding of living shoreline engineering guidelines. Using this background knowledge, site data acquired from the project site, and a cost analysis, multiple living shoreline designs were developed with an emphasis on a multifaceted solution that maximized the benefits and minimized the drawbacks of each design element. Upon further consideration of environmental impacts and possible implementation strategies, a final design was chosen that best fit the site.

The final living shoreline design for the City of Chelsea includes the following features: saltbush, switchgrass, American beachgrass, and coir logs on the bank, salt marsh and an oyster sill on the shoreline area, and reef balls in the nearshore area. This design not only mitigates erosion, but places an emphasis on the use of elements with carbon sequestration and water quality improvement capabilities. The implementation of the living shoreline was analyzed by developing a preliminary construction plan, listing key maintenance considerations, and conducting a permitting analysis. Both the federal and state permitting processes for this project are exempt from fees.

There are aspects of the design which could be expanded upon in the future. For example, while this project mainly involved using library research to obtain site data, laboratory tests and on-site measurements could be performed to obtain more accurate data. In addition, a more detailed cost analysis could be performed by acquiring quotes from local suppliers, as compared to averaging industry costs. Further analysis is likely needed concerning the sustainability of the living shoreline, particularly its resilience to storm surge and flooding events. As the City of

Chelsea establishes a more concrete plan for the park on the upland area of the site, efforts to integrate the living shoreline and park design should focus on stormwater management, allowing for eventual landward migration of the living shoreline, and equitable access to the living shoreline.

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Appendices

Appendix A: Project Proposal Report

Exploring Living Shoreline Alternatives at the Chelsea Street Bridge Parcel

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October 12, 2021

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3.6 Project Schedule and Final Deliverables	Jonathan	Julie
4.0 Conclusion	Jonathan	Evan

Capstone Design Statement

1.0 Introduction

The purpose of this study is to discover the most effective means to protect an area from sea level rise and catastrophic storms due to climate change, all while prioritizing an environmentally sustainable solution. Climate change and rising sea levels are a threat to coastal communities around the world, especially to the city of Chelsea, MA. Sources predict that sea levels have risen 0.14 inches per year in recent years and that this rate will only increase (Climate Change: Global Sea Level, 2021). Chelsea is a coastal city that borders Boston with a close-to-sea level elevation city wide. Chelsea has also been hit with many flood events in recent years, resulting in over 14 inches of rainfall and millions in property damage. (City of Chelsea Hazard Mitigation Plan 2014 Update, 2014) Because of these statistics, it is predicted that by 2070, about 50% of the city will see probable flooding during storms (Designing Coastal Community Infrastructure, 2017). Among these, important facilities to not only Chelsea, but the surrounding area, such as the Mass General Hospital could be at risk of flooding in the near future. In addition, the areas likely to be affected by flooding are low-income housing, the ethnicity of which is largely Hispanic. A coastal stabilization system along Chelsea Creek should be addressed immediately in order to preserve defenseless communities and valuable infrastructure.

In order to build coastal resiliency, communities often elect to implement “hard” or “gray” solutions like bulkheads or revetments. While effective at protecting against wave energy and flooding, “hard” coastal stabilization methods have several drawbacks, including: providing a short-term solution to a long-term problem, increased seaward erosion, reflected wave energy, decrease in biodiversity, and prevention of habitat migration.

An alternative to “gray” coastal stabilization methods is a living shoreline, which is a “green” approach. For the purposes of this report, living shorelines are defined as “a set of coastal erosion control practices, ranging from non-structural vegetated approaches to hybrid structural natural methods, that address erosion and flooding in a manner that improves or protects the ecological condition of the coastline” (Woods Hole Group, 2017). Examples of hybrid structural natural methods are oyster reefs, rock sills, or anchored wood. Living shorelines are a long-term solution to climate change, as they are able to raise their elevation with the sea level over time by trapping sediments from tidal waters. The environmental benefits of a living shoreline include improved water quality, habitat retention for shallow water fish and wildlife, increased biodiversity, natural marsh migration, and carbon sequestration.

Project Goal and Key Objectives

The goal of this project is to develop a living shoreline design for the city of Chelsea, Massachusetts to mitigate flooding and erosion along a section of Chelsea Creek by the Chelsea Street Bridge. This goal will be accomplished through the following four main objectives:

1) Research literature on living shorelines and the state of the industry
2) Characterize the existing site conditions and analyze future projections
3) Create multiple design alternatives for coastal stabilization
4) Identify a final design and analyze regulation and sustainability implications

2.1 Global Warming and Sea Level Rise

Global warming is defined as “the long-term heating of Earth’s climate system” (Climate Change: Global Sea Level, 2021). This trend is mostly due to human activity, wh

ich includes the burning of fossil fuels. This process began during the beginning of the industrialization period in the middle to late 19th century. When fossil fuels are burned, the emissions from these reactions are released into the atmosphere, which include compounds such as carbon dioxide. These unnatural levels of carbon dioxide act as an artificial blanket for Earth, as it disallows heat to escape back into space. This ever-thickening layer of emissions into the atmosphere is attributed to a rise of average global temperature of 1.8 degrees Fahrenheit since emissions began (Climate Change: Global Sea Level, 2021). This statistic also works in an exponential manner, so the global average temperature increase rate is projected to increase in the future (Figure 1).

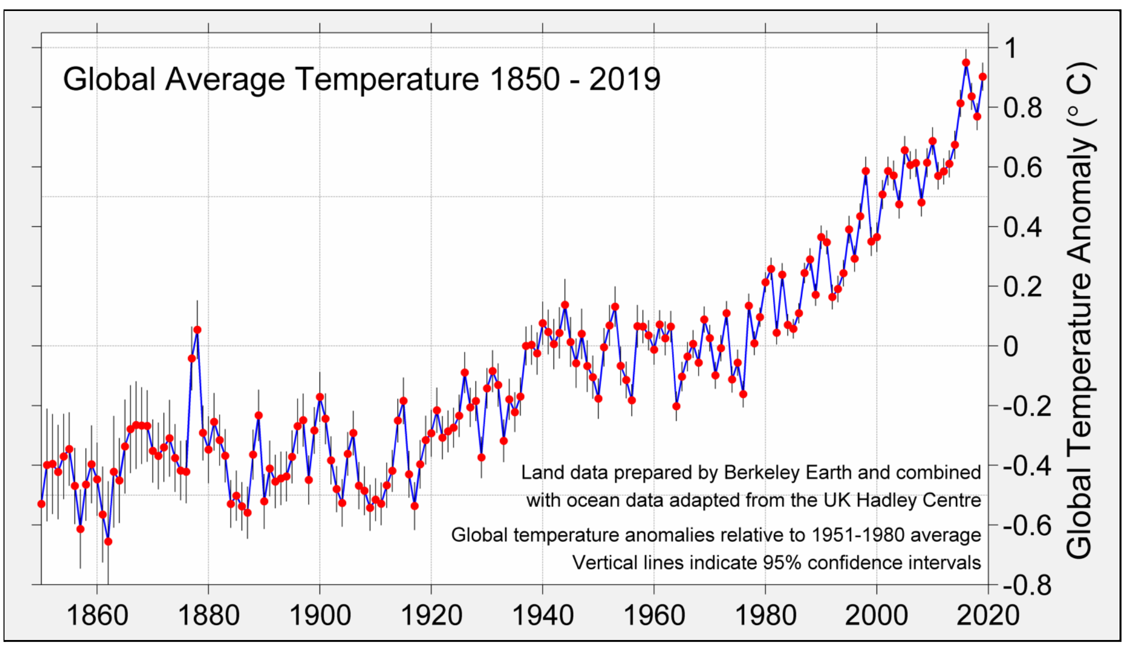

Figure 1: Global Average Temperature Since 1850. (Rhode, 2021)

One side effect of global warming is the melting of Arctic ice. In the past 30 years, ice in the Arctic has declined by 95% (World Wildlife Fund, n.d.). The melting of Arctic ice adds water to the oceans, which in turn causes a rise in sea level. Melting glaciers and ice sheets around the world also adds to this sudden rise. It is estimated that on average, global sea level has risen 8-9 inches since 1880 (Climate Change: Global Sea Level, 2021). Since this phenomenon is directly linked to global warming, the rate of global average sea level rise is also projected to increase in the future (Figure 2).

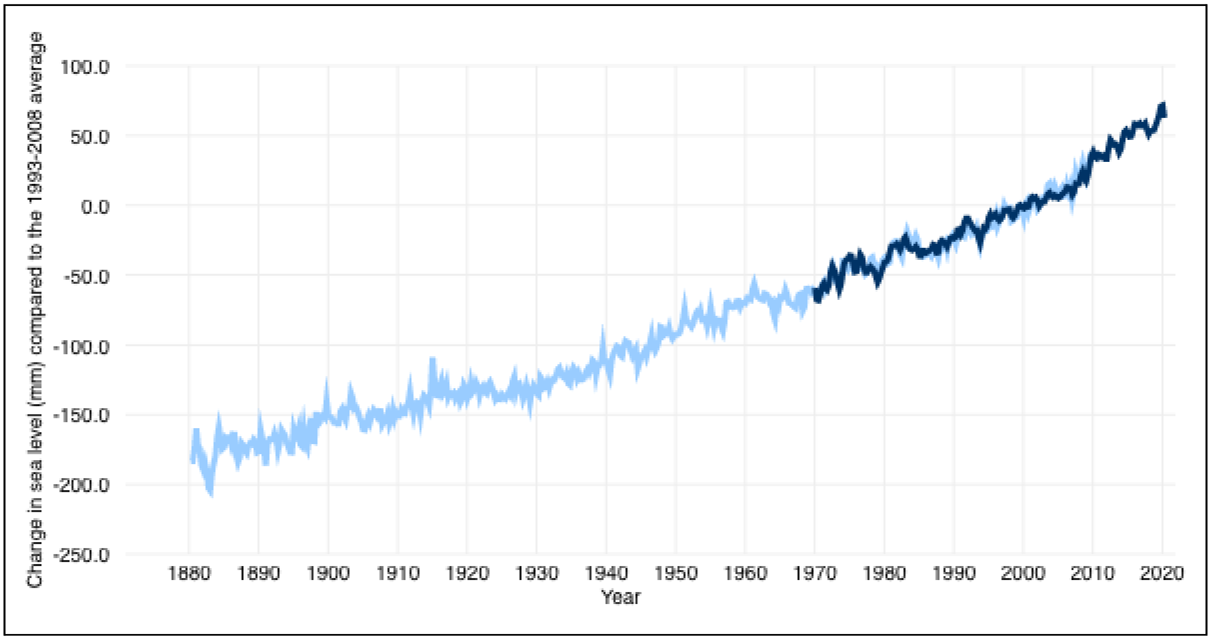

Figure 2: Global Sea Level Since 1880 (Climate Change: Global Sea Level, 2021)

Although this water being added to oceans causes them to rise, the higher temperatures due to global warming also contribute to thermal expansion. When the temperature of an object increases, the molecules that make up that object move around faster and more sporadically, which causes the object to swell in size. Although this change is relatively small, multiplying it across something as large as oceans leads to noticeable and dramatic increases.

Coastal communities are severely impacted by global warming and sea level rise. Multiple factors such as proximity to the ocean lead to more frequent and severe flooding, more storms, and a higher water table (U.S. Environmental Protection Agency, n.d.).

2.2 Background on the City of Chelsea

2.2.1 The History of the City of Chelsea

The City of Chelsea, Massachusetts, located across the Mystic River from Boston, has supported the local community for centuries. The land in and around the Chelsea waterfront was first used by Native Americans who hunted and harvested fish and shellfish. In the early 1600's, Europeans began to build permanent settlements in the vicinity of the planning area. Throughout the Colonial Period and through the years following the American Revolution, the area was largely farm and pasture land. A tide mill was built near the head of Chelsea Creek in 1721 and the tenant farmers in the area supplied milk and hay to Boston residents and supplied livestock, shellfish, and produce to outgoing vessels (*Proposed Chelsea Creek*, 2021). During the Industrial Period, Chelsea became known for its wooden shipbuilding industry and its oil, paint and varnish manufacturers (Chelsea, nd.). The population quickly increased post Civil War as Irish immigrants and Canadians from Nova Scotia began settling into the town (About our city, nd.). Over the next half century, due to its waterfront location and easy access to major cities via railroad, the City of Chelsea became a prime location for rapid industrialization. Manufacturers of rubber goods, paper boxes, and shoes became the city's leading industries. However, accelerated industrialization also led to many devistations, provoking many large fires that harmed the city as well as those living there. The most notable being the Great Chelsea Fire of 1908 that destroyed the city's waterfront, downtown and businesses, leaving many unemployed and over 18,000 people homeless (Chelsea, nd.). Over the course of 100 years, Chelsea endured over thirty significant fires, which may have potential effects on the city's ecosystems, wildlife habitats, air quality, and contribute to the increase in greenhouse gas emissions (Lake, C. C., 2011).

In addition to damages from large fires and air pollution, Chelsea is very vulnerable to flooding. The city is bordered by water on three sides, which is roughly 60 percent of its municipal boundary. The water surrounding the city consists of the Island End River, Mill Creek, Chelsea Creek, and the Mystic River (Bongiovanni, 2021). A significant portion of Chelsea's land was developed by filling salt marshes. Sitting at low elevations, these coastal areas are tidally influenced, with high groundwater tables and poorly draining soil. In addition, more recently pollution has reduced the remaining marsh areas along the coast. Therefore, Chelsea currently lacks the natural ability to alleviate flooding (*Proposed Chelsea Creek*, 2021). The city’s old infrastructure and lack of stormwater management also increase the city’s flooding vulnerability. (City of Chelsea community resilience building summary of findings, 2018). According to the City of Chelsea Hazard Mitigation Plan 2014, there have been 18 notable flood/storm surges from 1993 to 2014. Over the course of these two decades, coastal flooding and storm surges have caused the city millions of dollars in property damage. One of the most significant flood events occurred in March 2010 where a series of light to heavy rainfall occurred over a five week period. As seen in Figure 3, the eastern portion of Massachusetts received the highest amount of rainfall at the beginning of the rain period, ranging from 7-8 inches. Approximately 10.7 million dollars in property damage was caused (City of Chelsea Hazard Mitigation Plan 2014 Update, 2014). Continued flooding over time will only lead to further damage of the city’s infrastructure, destruction of land, and negative impacts on the people of Chelsea.

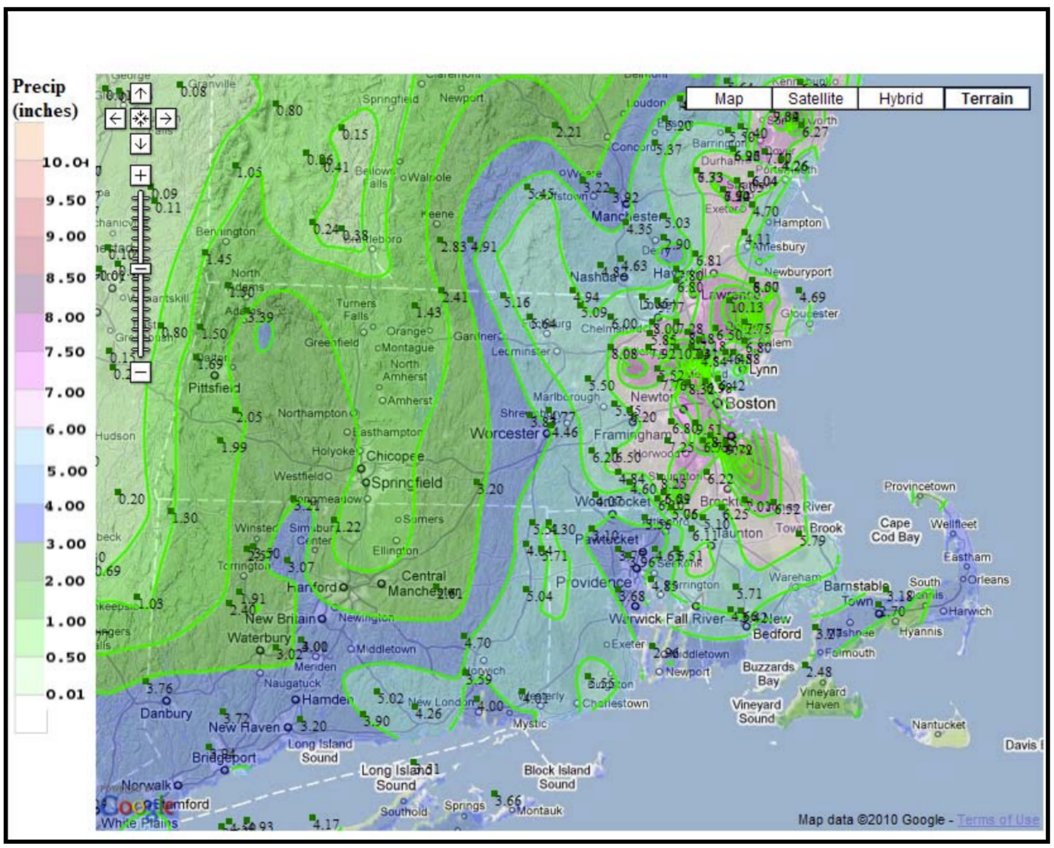

Figure 3. Rainfall in New England from March 13th to March 15th, 2010. (NOAA US Department of Commerce, 2021)

While Chelsea used to have extensive salt marshes and other natural resources, in 2013 the city was identified as the third most environmentally-burdened city in Massachusetts (*Proposed Chelsea Creek*, 2021). Oil remains a leading industry in Chelsea, with high demands for petroleum products, regional home heating oil, gasoline and jet fuel for the nearby Logan Airport (About the Chelsea Street bridge project, nd.). While oil products have greatly industrialized the city, it has also led to an increase in air pollution. Chelsea also provides road salt to 350 New England communities. The salt is stored in 50 foot tall piles along Chelsea Creek, much to the dismay of nearby residents. Traffic has become a large issue surrounding the Eastern Massachusetts area, with Route 1 and the Chelsea Street Bridge being the main routes to enter Boston. Vehicle emissions in this area have had significant impacts on the air quality in Chelsea and the health conditions of the people living there. According to the Massachusetts Environmental Public Health Tracking, asthma related hospital cases have notably increased (City of Chelsea community resilience building summary of findings, 2018).

The Chelsea Street Bridge is a vertical lift bridge that spans Chelsea Creek and connects Chelsea to East Boston and Logan Airport. The bridge was replaced in 2012 at a high cost to taxpayers, and it was promised that the new bridge would allow larger vessels to service Chelsea Creek. Larger vessels means fewer trips and less frequent bridge openings, thus less traffic. "Nine years later, that promise has not been realized nor is there a plan to realize it" (*Proposed Chelsea Creek*, 2021). Due to the high traffic of cargo carrying vessels, the bridge opens on average five to six times a day. To further compound the problem, the bridge openings are not scheduled ahead of time to allow commuters to plan their trips. Figure 4 illustrates bridge openings over 40 days from late August to early October 2018 (*Proposed Chelsea Creek*, 2021).

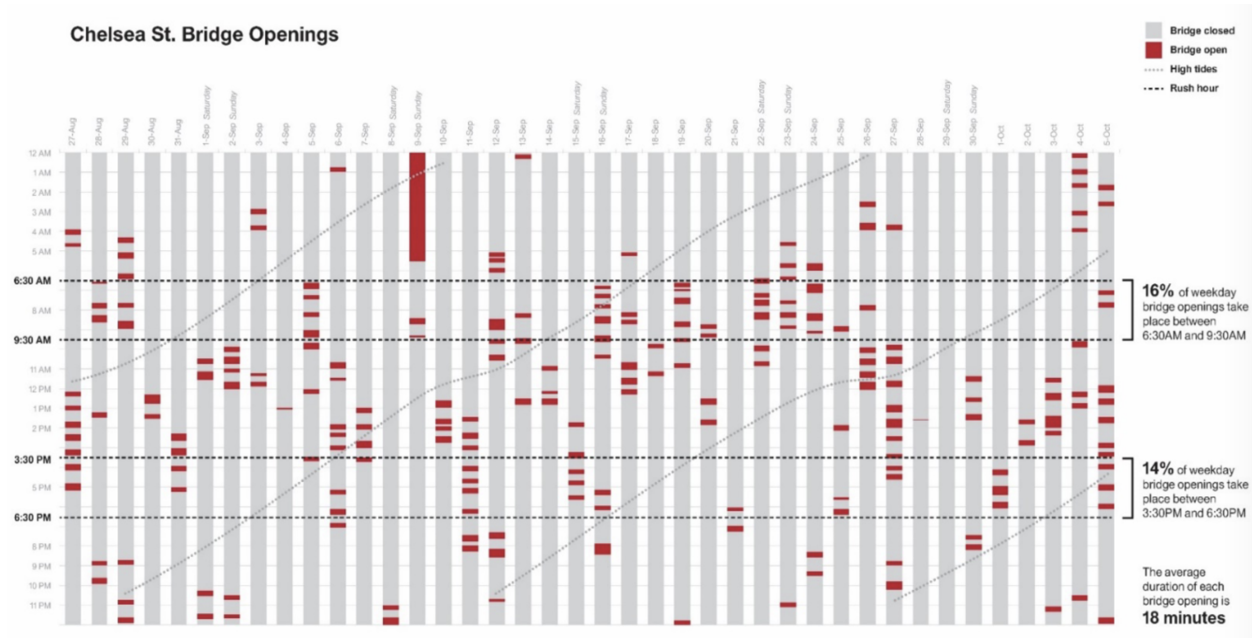

Figure 4: Chelsea Street Bridge Openings from Late August to Early October in 2018. (*Proposed Chelsea Creek*, 2021)

2.2.2 The City of Chelsea's Demographics

Chelsea has a population of approximately 40,000 people (Bureau U.S.C., 2021). Considering the city has only 2.1 square miles of land, it is densely populated, as are most suburbs outside of larger cities. 67% of people in Chelsea identify as Hispanic or Latino, which is the second largest percentage of such ethnicity in Massachusetts behind the town of Lawrence (Bureau, U.S.C., 2021). The specific spots of settlement may tie into the fact that this group of people have a higher social vulnerability to flooding (Climate Central). For example, as shown in Figure 5, the only section of Chelsea that is not predominantly Hispanic or Latino is not prone to flooding due to the area's higher elevation. The majority of the area affected by flooding is low-income housing that is close to the shoreline or at particularly low elevations (Figure 6). In the future these communities will be at an even higher risk as the prediction of probable flooding is slated to increase in the future (Designing Coastal Community Infrastructure, n.d.). Likely as a result of poor environmental conditions from industrial activity, Chelsea residents also have high rates of lead poisoning, cancer, asthma, and cardiovascular disease. Chelsea residents are classified as an environmental justice population, meaning that they are most at risk of being unaware of or unable to participate in environmental decision-making or to gain access to state environmental resources (*Proposed Chelsea Creek*, 2021).

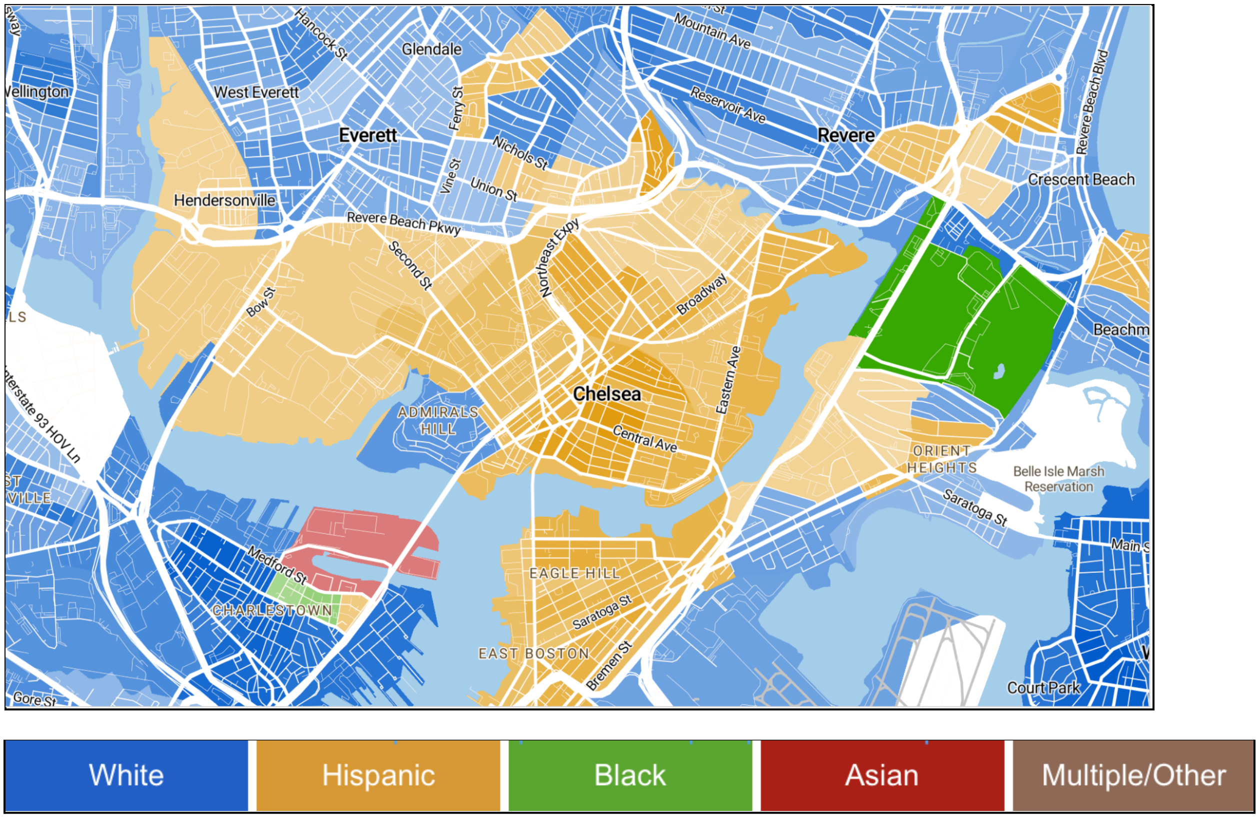

Figure 5: Race Population Map for Chelsea, MA. (Race Map for Chelsea, MA and Racial Diversity Data, n.d.)

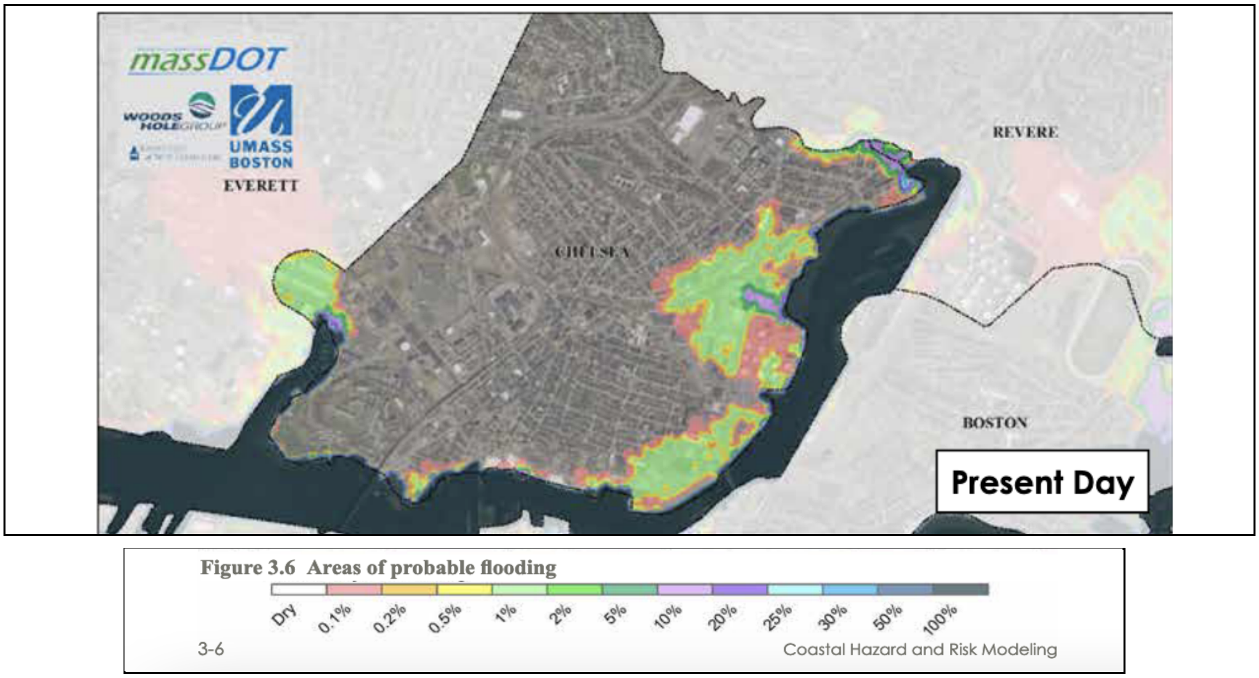

Figure 6: Present Day Flooding Risk for Chelsea, MA. (Designing Coastal Community Infrastructure, n.d.)

2.2.3 General Information on Chelsea Creek

Chelsea Creek is a 1.8 mile long, highly engineered, tidal river. Its waterfront mostly consists of active industrial activities and underutilized land contaminated by past industrial use, as seen in Figure 7. Chelsea Creek serves the commercial needs in Chelsea, East Boston, and Revere, and has seen an increase in large vessel traffic over the last several years. The channel is currently 38 feet deep and approximately 225-250 feet wide from the McArdle Bridge to the Chelsea Street Bridge. From the Chelsea Street Bridge to a point near the creek's end, the channel is 250-430 feet wide. The Boston Harbor Improvement Project plans to further deepen and widen Chelsea Creek to accommodate large vessels, but currently there is no funding or scheduling for the project. Chelsea Creek faces water quality issues, largely from polluted runoff. The city of Chelsea has an impervious cover of 75% and very little green space. Because of this, Chelsea Creek receives stormwater inputs containing urban contaminants from runoff in Chelsea, East Boston, Revere, and Everett (*Proposed Chelsea Creek*, 2021).

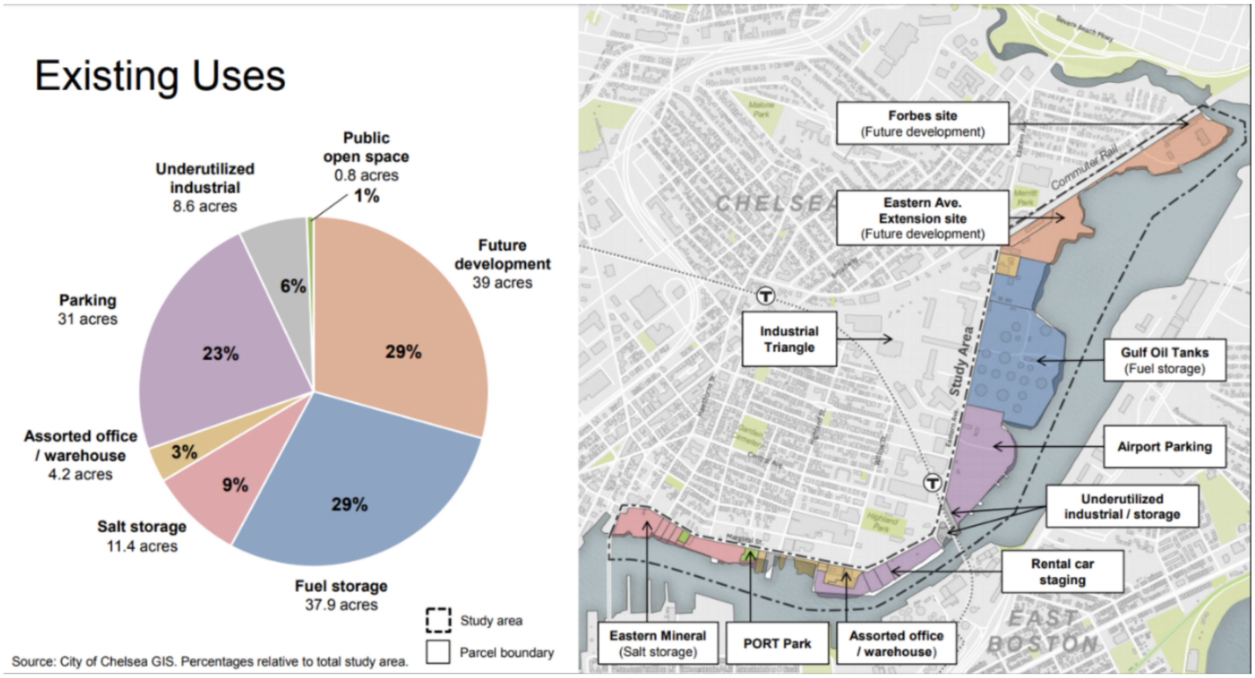

Figure 7: Existing Land Uses Along Chelsea Creek Waterfront. (*Proposed Chelsea Creek*, 2021)

Public and environmental action around Chelsea Creek has been high for the last decade. Local communities feel they have been long prevented from rightful access to the creek's waterfront due to the industrial nature of the region. The City of Chelsea has plans to create multiple points of access along the creek filled with public art, temporary retail, and public programming. Some of the ideas for these initiatives include pop-up markets, seasonal retail, outdoor movies and entertainment, and food trucks (*Proposed Chelsea Creek*, 2021). With the declining health of the natural shoreline of Chelsea Creek and increased chance of flooding, there have been numerous reports and meetings between public and private stakeholders around building the city's climate resiliency. It is evident from these reports and meetings that multi-faceted and sustainable solutions are needed for Chelsea Creek's shorelines.

2.3 What is a Living Shoreline?

Living shorelines, also known as "green shores" or "ecologically enhanced shorelines", are a green infrastructure approach to shoreline protection contrary to traditional "hard" shoreline stabilization measures such as bulkheads and revetments. Originally developed in the Chesapeake Bay area two decades ago, living shorelines have gradually gained momentum and spread nationwide (Miller et al., 2015). Living shorelines are created by planting native wetland plants, wetland grasses, shrubs, and trees at various points along a shoreline (U.S. Department of Commerce, 2019). While attempting to mimic the habitat of a natural shoreline as closely as possible, living shorelines typically differ from natural shorelines in two elements. One being that living shoreline plantings are done on a grid, making the initial plant density controlled by design not flooding. The second element is that living shorelines have a constant gradual slope, while natural shorelines often have an eroded edge and complex microtopography (Mitchell, 2019). Living shorelines can be installed on freshwater and saltwater coasts, wherever erosion is present (Living Shorelines, 2021). In addition to resisting erosion, living shorelines have the ability to adapt to rising water levels and increased storm activity due to climate change by trapping sediments from tidal waters. In areas with high wave energy, organic materials such as fiber mats and oyster shells can serve as breakwaters and reduce the energy to a level where the native vegetation can absorb the rest.

Living shorelines can be entirely natural, but in some cases a hybrid system is needed. Natural living shorelines are typically used in lower energy environments, such as estuaries or lakes. They include native vegetation like marsh grasses and reefs and biodegradable materials like logs made from coconut fibers. On the other hand, hybrid living shorelines are used in lower to moderate energy environments, like bays or some open-ocean coastline. Hybrid systems have both “soft” (natural) and “hard” (manmade) components. They can incorporate native vegetation or biodegradable organic materials with low-profile rock structures or bulkheads (Living Shorelines, n.d.).

2.4 Living Shorelines vs. Structural Shorelines

When it comes to coastal flooding mitigation, there are many different strategies to keep water away from desired areas. Traditionally, structures made of concrete or stone were built to act as a wall against a body of water. Bulkhead, a vertical wall placed next to a body of water designed to hold soil in behind it and keep water out in front of it, falls into this category (Fisheries, NOAA, n.d.). This structure can also counteract erosion. A revetment is another common fix in coastal communities, which acts like a wall but uses boulders or riparian instead and lays on the shoreline itself (Fisheries, NOAA, n.d.). This material can also be extended into the ocean in order to create a breakwater, which disrupts tidal patterns in an effort to lessen the blow of waves and currents on the shoreline. These strategies can be classified as coastal structures.

On the other hand, living shorelines can achieve the same goals but with sustainability at the forefront of design. Living shorelines provide a "green" alternative to "gray" shoreline stabilization methods like riparian or bulkheads. A spectrum of "green" to "gray" shoreline stabilization approaches, and their general intended use, can be seen in Figure 6.

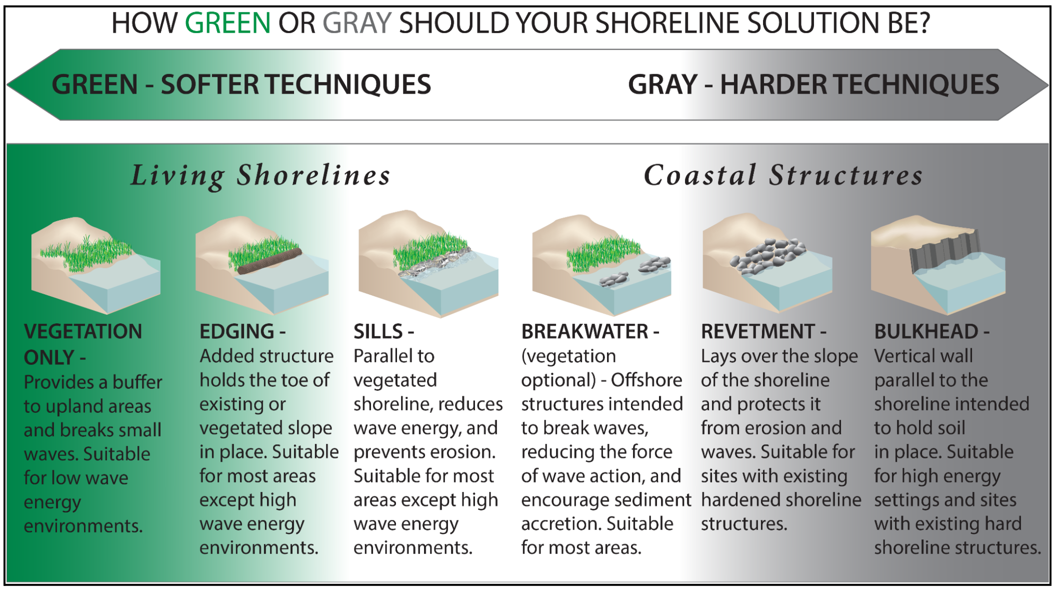

Figure 8: "Green" to "Gray" Spectrum of Shoreline Stabilization Methods. (Living Shorelines, n.d.)

Living shorelines are dynamic with the surrounding environment, unlike bulkheads which are static systems and thus short-term solutions to climate change. Marshes trap sediments from tidal waters, allowing them to raise their elevation with the sea level and thus prolong their effectiveness as a shoreline stabilization method. Living shorelines encourage natural marsh migration, while hard shoreline structures prevent sediment collection and may create seaward erosion. In addition, living shorelines are generally more cost effective for construction and in the long-term, as they are self-sufficient once developed and don't require costly repairs or additions like bulkheads. According to a comprehensive study on material costs, living shorelines range from $50–$150 per linear foot based on the type of living shoreline. By comparison, the same analysis for bulkheads produced a cost range of $80–$1200 per linear foot

(Living Shorelines, n.d.). Another major benefit of living shorelines is that they absorb wave energy, rather than reflecting it like bulkheads. Reflected wave energy results in scour offshore of the system, deepening of the water, and loss of offshore vegetation (U.S. Department of Commerce, 2016). Other benefits of living shorelines include improved water quality, habitat retention for shallow water fish and wildlife, increased biodiversity, and carbon sequestration. One square mile of salt marsh can store the carbon equivalent of 76,000 gal of gas annually (U.S. Department of Commerce, 2019). Water quality is improved because the roots of the living shoreline plants filter and slow harmful runoff from adjacent lands, thus reducing the amount that reaches the body of water.

While the advantages of a living shoreline approach are numerous, their disadvantages should be explored as well. The major drawback of living shorelines is that their effectiveness is largely dependent on the existing environment. For example, living shorelines are not effective for steep-sloped or deep water coastlines, or coasts consistently exposed to high wave energy. In addition, living shorelines require larger areas of land as compared to hard shoreline stabilization methods, thus resulting in more permitting issues. Living shorelines also require extensive planning and environmental knowledge prior to construction, as questions as such need to be addressed: what is the native soil type, what wildlife are in the existing area, how much foliage needs to be kept/removed/added, which plants need more sunlight, which areas stay dry or wet? It's important to note that living shorelines are engineered systems, thus they frequently contain structures designed to mitigate wave energy which can disrupt sedimentation and faunal settlement patterns (Mitchell, 2019). Finally, while living shorelines are self-sustaining in the long term, it takes 2-3 years of costly and time-consuming maintenance like fertilizing and replanting to ensure the system is growing appropriately (U.S. Department of Commerce, 2016).

2.5 Engineering Guidelines for Living Shoreline Design

As previously mentioned, the effectiveness of living shorelines to control erosion and act as a barrier to sea level rise is largely dependent on the site conditions. Different types of living shorelines will be more suitable depending on the project, and in some cases a living shoreline approach may have to be abandoned altogether. In addition, living shoreline projects are usually diverse, thus each project may have its own set of unique factors to consider.

When determining a project's shoreline stabilization method, system, ecological, hydrodynamic, and terrestrial parameters should be taken into account, along with additional considerations like permitting and constructability. Professionals in the Davidson Laboratory Center for Maritime Systems at Stevens Institute of Technology extensively analyzed each set of parameters, defining their importance in determining a shoreline stabilization approach and also providing quantitative ranges for each factor to streamline the decision-making process (Miller et al., 2015). The system parameters that these professionals established were erosion history, sea level rise, and tidal range. Ecological parameters consisted of water quality, soil type, and sunlight exposure. Hydrodynamic parameters covered wind waves, wakes, currents, ice, and storm surge. Terrestrial parameters included upland slope, shoreline slope, width, nearshore slope, offshore depth, and soil bearing capacity. Additional considerations were permits and regulations, end effects, constructability, native and invasive species, debris impact, and project monitoring (Miller et al., 2015). The appropriate conditions for various living shoreline approaches and the consequent criteria ranges can be seen below in Figure 7 and Figure 8, respectively.

	Marsh Sill	Breakwater	Revetment	Living Reef	Reef Balls
System Parameters					
Erosion History	***Low-Med***	***Med-High***	***Med-High***	***Low-Med***	***Low-Med***
Relative Sea Level	Low-Mod	Low-High	***Low-High***	Low-Mod	Low-Mod
Tidal Range	***Low-Mod***	Low-High	Low-High	***Low-Mod***	Low-Mod
Hydrodynamic Parameters					
Wind Waves	***Low-Mod***	***High***	***Mod-High***	***Low-Mod***	***Low-Mod***
Wakes	***Low-Mod***	***High***	***Mod-High***	***Low-Mod***	***Low-Mod***
Currents	Low-Mod	Low-Mod	Low-High	Low-Mod	Low-Mod
Ice	***Low***	***Low-Mod***	***Low-High***	***Low***	Low-Mod
Storm Surge	Low-High	***Low-High***	***Low-High***	Low-High	Low-High
Terrestrial Parameters					
Upland Slope	Mild-Steep	Mild-Steep	***Mild-Steep***	Mild-Steep	Mild-Steep
Shoreline Slope	***Mild-Mod***	***Mild-Steep***	**Mild-Steep**	***Mild-Mod***	Mild-Steep
Width	***Mod-High***	***Mod-High***	Low-High	***Mod-High***	***Mod-High***
Nearshore Slope	***Mild-Mod***	***Mild-Mod***	Mild-Steep	***Mild-Mod***	***Mild-Mod***
Offshore Depth	Shallow-Mod	Mod-Deep	Shallow-Deep	Shallow-Mod	Shallow-Mod
Soil Bearing	Mod-High	***High***	***Mod-High***	Mod-High	***Mod-High***
Ecological Parameters					
Water Quality	Poor-Good	Poor-Good	Poor-Good	***Good***	***Poor-Good***
Soil Type	***Any***	Any	Any	Any	Any
Sunlight Exposure	***Mod-High***	Low-High	Low-High	Mod-High	Low-High

Figure 9: Engineering Parameter Conditions for Various Living Shoreline Designs. (Miller et al., 2015)

Parameter	Criterion Low/Mild	Moderate	High/Steep
System Parameters			
Erosion History	<2 ft/yr	2 ft/yr to 4 ft/yr	>4 ft/yr
Sea Level Rise	<0.2 in/yr	0.2 in/yr to 0.4 in/yr	>0.4 in/yr
Tidal Range	< 1.5 ft	1.5 ft to 4 ft	> 4 ft
Hydrodynamic Parameters			
Waves	< 1 ft	1 ft to 3 ft	> 3 ft
Wakes	< 1 ft	1 ft to 3 ft	> 3 ft
Currents	< 1.25 kts	1.25 kts to 4.75 kts	>4.75 kts
Ice	< 2 in	2 in to 6 in	> 6 in
Storm Surge	<1 ft	1 ft to 3 ft	>3 ft
Terrestrial Parameters			
Upland Slope	<1 on 30	1 on 30 to 1 on 10	>1 on 10
Shoreline Slope	<1 on 15	1 on 15 to 1 on 5	> 1 on 5
Width	<30 ft	30 ft to 60 ft	>60 ft
Nearshore Slope	<1 on 30	1 on 30 to 1 on 10	>1 on 10
Offshore Depth	< 2 ft	2 ft to 5 ft	> 5 ft
Soil Bearing Capacity	< 500 psf	500 psf - 1500 psf	> 1500 psf
Ecological Parameters			
Water Quality	-	-	-
Soil Type	-	-	-
Sunlight Exposure	<2 hrs/day	2 to 10 hrs/day	>10 hrs/day

Figure 10: Data Ranges for Different Engineering Parameter Conditions. (Miller et al., 2015)

Most of the factors above are self-explanatory in terms of their significance with living shorelines, but some are more obsolete. The parameters with less obvious impacts on living shoreline design will be briefly explained below.

Tidal range, a system parameter, is key for submerged or low structures such as sills or small breakwaters. The position of the top of the structure relative to the water level plays a role in the amount of energy dissipation and thus the amount of force on the structure. Tidal ranges are also important for the selection of the appropriate vegetation and the growth of reef elements like mussels and oysters (Miller et al., 2015). In addition, tidal ranges have a large effect on a site's sediment supply, as sediment collection increases with time underwater. Due to rapid sea level rise, some living shorelines may need augmented sediment supplies. One method for doing this is a thin-layer dredge disposal, where a thin deposit of sediment is sprayed over the shoreline in the hope that it will grow the existing marsh. However, this method has only been used on natural marshes, and it's effectiveness on living shorelines needs to be studied (Mitchell, 2019).

The hydrodynamic parameters wind waves, boat wakes, and currents are critical in determining the living shoreline type for a project. The size of wind waves are determined by wind speed, wind duration, and the open water distance over which it acts, or fetch. In most coastal engineering applications, the maximum expected wave is used for design. However, the maximum expected wave may not represent the critical condition for living shorelines because a large storm could submerge the entire project. As boats pass, two distinct types of wake waves are generated. Divergent waves, typically generated by large and slow moving ships, are from the bow of the boat. Transverse waves, typically generated by small and fast moving ships, are from the stern and propellers. The largest wakes are generated at the point where the two types of waves intersect. Unfortunately, "wakes are rarely...taken into account during design in a physically satisfying manner, due to a lack of readily available wake measurements" (Miller et al., 2015). Currents are particularly critical for living shoreline sites located near tidal inlets or along riverbanks. Currents have the capacity to uproot vegetation, scour the bank, and transport debris during storms or ice in areas subject to freezing, thus increasing the scour potential (Miller et al., 2015).

Terrestrial parameters such as width, nearshore slope, and soil bearing capacity demand significant attention when designing a living shoreline. Along developed coastlines, the width, or horizontal space between the developed area and the water's edge, is often reduced or eliminated. Large available project widths are conducive to the long term success of living shorelines, as they provide more potential for upland marsh retreat (Mitchell, 2019). However, when space is not available, two options exist for creating it. The first is to landscape back into the site at an appropriate slope, and the second is to build out the shoreline through the use of fill. In most states, there are strict regulations prohibiting the placement of fill below the mean high water line. Fortunately, the "Living Shorelines General Permit (GP 24) provides an exception for wetland restoration projects...for the purposes of habitat enhancement" (Miller et al., 2015). A site's nearshore slope determines the behavior of the waves and currents immediately offshore. Steeper slopes generally reflect energy, while milder slopes tend to absorb and dissipate energy. In addition, steep nearshore areas will require more fill and may also make structures less stable. Soil bearing capacity is an often overlooked factor in the design of living shorelines projects. The majority of living shoreline projects are constructed in areas with poor soil conditions according to traditional construction standards. Even though the size of the materials used in living shorelines projects is small compared to traditional "hard" stabilization approaches, the additional load imposed by stone, concrete, or even natural reefs needs to be taken into consideration to avoid undesired settlement (Miller et al., 2015).

One ecological parameter is sunlight, which is vital to the development of both aquatic and terrestrial habitats. Photosynthesis only occurs in the presence of sunlight, which directly affects water quality and the level of aquatic and terrestrial biological production (Miller et al., 2015). Shade from trees can not only slow habitat development and migration, but can also raise competition from invasive species (Mitchell, 2019).

2.6 Living Shoreline Permitting Process

The permitting process for living shorelines has historically been complicated and largely dependent on the region of implementation. However, in 2017, the Army Corporation of Engineers authorized Nationwide Permit 54 to make the construction of living shorelines easier across the United States. The conditions for creating a living shoreline under permit 54 are that the project cannot extend more than 500 feet along the shoreline, cannot extend more than 30 feet below the mean low water level, structural materials must be anchored to prevent relocation, native plants appropriate for site conditions should be used with a minimum necessary discharge, there should be minimal adverse effects to water and organism movement, and the living shoreline must be properly maintained. The permit can be obtained from the local Army Corps of Engineers office in the district (Woods Hole Group, 2017).

Nationwide Permits (NWPs) are a category of general permits administered by the Army Corps and traditionally updated every five years. General permits can be designed and issued at a state scale, a regional scale, or a national scale. Permit conditions vary between states because they can add specific considerations to general permits “so that they can be more quickly processed and approved, minimizing the burden on both the applicant and the regulators” (Woods Hole Group, 2017). The boards in Massachusetts that may be involved with regulation and review are the Local Conservation Commission, Massachusetts Division of Fisheries and Wildlife (Natural Heritage and Endangered Species Program), Massachusetts Environmental Policy Act, and Massachusetts Office of Coastal Zone Management.

2.7 Living Shoreline Case Studies in New England

Living shorelines have been used all across the United States, but they have been extensively used in the Chesapeake Bay area in Maryland. Their construction has been encouraged by the state in order to help stop shoreline erosion and help stem the impacts of flooding. Originally hard methods of stopping soil erosion, like bulkheads and seawalls, were used, however due to the fact that they reflect the wave energy out they continued to cause erosion and did not stop the issue. “In 2008, the Maryland Legislature passed the Living Shoreline Protection Act, requiring shoreline property owners to use natural solutions to prevent erosion unless they can prove that such methods would not work on their property” (Maryland’s ‘Living Shorelines’, n.d.). In passing this act, Maryland switched to using soft methods of shoreline erosion prevention that don't reflect the wave energy but absorb and disperse it, as well as help to root sand and sediment in place.

There have also been several different types of living shorelines that have been implemented across New England. A natural marsh style living shoreline was created at a site at Sachuest Point in Middletown, Rhode Island. It was able to be planted, but needed maintenance on fences to protect against grazing geese for much of the winter. In addition, a gentler slope for the marsh would be beneficial to deal with the ice, as well as incorporating more shrubs and tall plants which would help to break up the ice.

There was also a project using a living breakwater design in Stratford, Connecticut (Figure 11). This had rock outcroppings installed along in order to support oyster colonies. There are some concerns with these about invasive species of oysters or other species using the reefs to settle. The other concern this site faced was the tidal range had to be carefully considered as the reefs were placed in an area where the oysters were at risk of being exposed above the water and freezing and dying during the winter.

There have also been potential living shoreline ideas proposed and planned for the local Chelsea area. The Vision Chelsea Creek project had a proposed plan for the implementation of a living shoreline on an area along the Chelsea Creek. The plan was a detailed assessment of the potential to implement specific types of living shorelines, including shoreline restoration, which is good evidence that similar projects have been researched and considered for the local Chelsea area (*Living Shorelines,* 2017).

Figure 11: Reef Ball Breakwater in Stratford, Connecticut. (*Living Shorelines in New England,* 2017)

A study of increasing coastal resiliency and mitigating shoreline erosion at Coughlin Park was conducted in 2016 by Woods Hole Group. Coughlin Park is located on the bayside of Winthrop Barrier in Winthrop Massachusetts, which is just east of Boston's Logan Airport. The study researched the existing conditions at the site and proposed several entirely green and hybrid living shoreline designs. For each design alternative, advantages and disadvantages were presented. For example, the idea of using cobble berms was suggested, which would involve using mounds of cobble at the toe of the coastal bank (Figure 12). The loose cobble would help to break apart the wave energy and would also be able to move slightly, allowing itself to adjust to natural patterns in the water. There are also negatives with its loose structure, mainly that it will require maintenance and some replacement of the cobble as some will be lost over time. They also looked into the use of coir logs, which are rolls of coconut fiber, at the toe of the beach to add a buffer between the toe of the beach and incoming wave energy. This helps stabilize the bank and makes it easier for plant life to grow in the area. The drawbacks of this approach are because the coirs are biodegradable, they will naturally break down rather quickly, with an expected lifespan of five to eight years depending on the wave energy of the site (*A Plan to Increase Coastal Resiliency at Coughlin Park*, 2016).

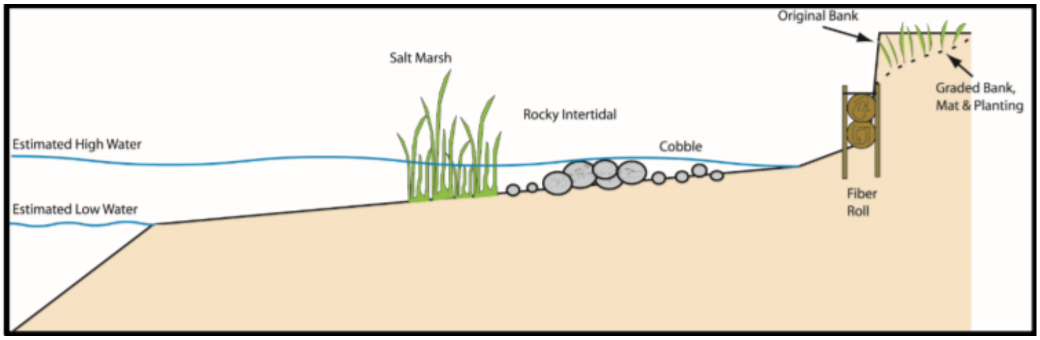

Figure 12: Diagram of Living Shoreline Design at Coughlin Park with Cobble and Coir Rolls. (*A Plan to Increase Coastal Resiliency at Coughlin Park,* 2016)

This case study highlighted the importance of a multi-faceted approach to living shoreline design in order to address all design factors. Their final design consisted of a combination of fiber rolls, bank grading and planting, cobble bank nourishment, and cobble berm. This case study also detailed an interagency coordination meeting that was held on-site to discuss the project. The agencies in attendance were the Massachusetts Department of Marine Fisheries, Coastal Zone Management, Massachusetts Department of Environmental Protection, Winthrop Conservation Commision, Winthrop Department of Public Works, US Army Corps of Engineers, Woodard and Curran, and Woods Hole Group. The large number of public and private entities involved in this project illustrates how crucial interagency collaboration and consideration of multiple perspectives is when reconstructing a shoreline. It also underscores the complexity of settling on a final design that satisfies environmental, engineering, and public needs (*A Plan to Increase Coastal Resiliency at Coughlin Park*, 2016).

3.0 Methodology

3.1 Introduction

The goal of this project is to develop a living shoreline design for the city of Chelsea, Massachusetts to mitigate flooding and erosion along a section of Chelsea Creek near the Chelsea Street Bridge. In order to achieve this goal, we will:

1) Research literature on living shorelines and the state of the industry
2) Characterize the existing site conditions and analyze future projections
3) Create multiple design alternatives for coastal stabilization
4) Identify a final design and analyze regulation and sustainability implications

The details of each strategy are outlined below.

3.2 Objective 1: Research Literature on Living Shorelines and the State of the Industry

Before thinking about potential solutions for the Chelsea Street Bridge coastline, an understanding of the concept of living shorelines, general engineering guidelines, and industry trends needs to be established. For example, a holistic summary of the advantages and disadvantages of living shorelines will provide a base knowledge necessary for trying to maximize the benefits and minimize the drawbacks. In addition, we will identify which environments are generally conducive for certain types of living shorelines. This will serve as a sanity check later in the project when we are selecting design alternatives based on collected data. It is critical to have knowledge of the scope of engineering guidelines for living shorelines projects, regardless of type. Furthermore, we will formulate a list of key "do's" and "don'ts" in living shoreline design. Other information that will be obtained through research of the concept of living shorelines will be planting considerations, maintenance, and permitting.

Once the concept of living shorelines is understood, we will begin research on the state of the living shoreline industry, from both a global and regional scale. This step in our research is essential to ensuring that we are aware of current industry trends. This will give us a broad sense of the feasibility of the project and major barriers to address. Sources such as the National Oceanic and Atmospheric Administration (NOAA) and Woods Hole Oceanographic Institution will be used to further our understanding of which parameters are necessary to analyze. First, a brief literature review will be conducted of the history, progression, and future trends of the global industry. General cost comparisons between different living shorelines systems and between living shorelines and “hard” coastal stabilization methods will be attained. Major barriers to living shoreline implementation, such as strict coastal regulations, will be identified. Government and private funding will also be researched, along with public acceptance. Once an understanding of the global industry is established, research will be focused on the New England area. The level of funding and acceptance of living shorelines in this region will be analyzed. Case studies in Massachusetts and nearby locations will be reviewed, thus revealing common methods of design and barriers unique to New England.

3.3 Objective 2: Characterize the Existing Site Conditions and Analyze Future Projections

Insight into general living shoreline advantages and disadvantages, the benefits and limitations of different designs, engineering guidelines, and state of the industry will be gained through the first objective. For the second objective, we will use the research of engineering guidelines to develop a list of design factors that we will focus on in this project. This objective also involves how we will obtain data for each factor. When designing a living shoreline, a wide range of factors need to be considered. There are five major categories of factors that must be considered: system, hydrodynamic, terrestrial, ecological, and additional considerations (Miller et al., 2015). For illustrative purposes, tools and means to achieve data can be explored for essential design factors of a living shoreline.

The key system parameters we are examining in our design include erosion history, sea level rise, and tidal range. For data on erosion history, online geographical information programs are available for public use. These programs include *Google Earth*, Nationwide Environmental Title Research (NETR) database, GIS Data Repositories, and the NOAA Lidar Dataset. We will use these programs to obtain satellite imagery, historic aerial photographs, and topographic maps and observe the land over the course of many years. From this data we will be able to target certain areas that may need more protection from flooding than others. For the sea level rise, data on the sea level projection is readily available online using Risk Finder. This website is able to provide data reports as well as maps of the predicted flooding areas in the next several years. Lastly, for tidal range data, we will begin by utilizing the NOAA’s VDatum tool, which is a software that can transform geospatial data among tidal datums. However, this tool is prone to significant errors, so we will also be using the NOAA's Computational Techniques for Tidal Datums Handbook to perform our own analysis (Miller et al., 2015).

The key hydrodynamic parameters in our design include wind waves, wakes, currents, and storm surge. For an analysis of wave conditions, two types of methods will be explored. The first method uses a chart to relate relative energy at the site of the fetch and the second uses the SMB method which factors in wind conditions. Data for both of these methods can be found on online databases such as Windfinder. Quantitative data on boat wakes is difficult to find online, so if possible, our group can perform a visual analysis on-site using a graduated rod. The rod will be fixed to a structure along with a camera to monitor the water surface oscillations. This analysis would ideally be repeated multiple times along the perimeter of the creek to ensure the most accuracy. It should be noted that the resource and time constraints of this project will only allow us to obtain a sample size of data that will not accurately characterize all boat wakes. For currents, general data can be obtained from online sources like the NOAA, NYHOPS, and USGS, where detailed hydrodynamic models exist. Finally, the last parameter we will examine are storm surges, which are typically overlooked when designing a living shoreline due to its low positioning. Existing information, like the FEMA Flood Information Study reports and Flood Insurance Rate Maps (FIRMS), are easily attainable and will provide a general analysis of the storm surges. Other resources such as the NOAA also provide estimates of extreme water levels that don't take into account wave effects (Miller et al., 2015).

The key terrestrial parameters in our design will likely be upland slope, shoreline slope, nearshore slope, offshore depth, site width, and soil physical and mechanical properties. For the slope factors located above the water level (upland slope and shoreline slope), relatively accurate and readily available information exists online. Topographic maps, digital elevation models (DEMs), and Lidar data sets will be explored. For the slope factors located below the water level (nearshore slope and offshore depth), data is more crudely presented. While many freely available bathymetry data sets exist online, the resolution is often insufficient for final design purposes (Miller et al., 2015). Nevertheless, due to the budgetary constraints of this project, the nearshore slope and offshore depth will be estimated from bathymetry data sets. Site width, the horizontal space between the developed area and the water's edge, will be attained through both a physical measurement on a site visit and by using the measure tool on *Google Earth*. Soil properties, an important but often overlooked factor, requires a multi-faceted analysis in order to have an understanding of the soil strength and behavior. In an ideal scenario, we would take several samples back to the WPI laboratories to perform direct shear tests to reveal the strength properties of the soil. Unfortunately, laboratory equipment to perform such tests are currently unavailable. Thus, we will conduct the following multi-step analysis. We will first determine if there are any available published geotechnical studies and dredging records for Chelsea Creek near the site location. If no data is available, then we will conduct our own investigation of soil properties. Each of the following steps will be conducted at different locations relative to the water level. First, during a site visit, pictures will be taken of the soil. Second, a thumb penetration test will be performed on-site to estimate the compressive strength of the cohesive soils (clays, silts, sandy clay, clayey silt, etc.) Third, if readily available, a hand penetrometer, a pocket-sized device that measures the pressure a soil can resist, will be used to estimate the soil bearing capacity.

The key ecological parameters in our design will be water quality and sunlight exposure. Water quality is graded based on factors like dissolved oxygen concentrations, water temperature, salinity, and turbidity (Miller et al., 2015). We will take advantage of the many publicly available reports on water quality in the Greater Boston area. One example of a report we will use in our assessment of water quality will be the 2019 Mystic River Watershed Report Card, created by the Mystic River Watershed Association. Sunlight exposure will be analyzed by using *Google Earth*. The results from *Google Earth* will be checked by a field survey when we visit the site. This survey should be done when vegetation is at its fullest.

Additional considerations include exploring regulations, native and invasive species for the area, constructability, end effects, and project monitoring. We will base our analysis of regulations and permitting on the City of Chelsea parcel maps for the Chelsea Street Bridge area. From the parcel maps, we can identify land ownership and the nature of surrounding land use. We will also identify the key stakeholders in coastal reconstruction projects in the area by analyzing past living shoreline projects in Massachusetts. For native and invasive species, we will take pictures of the existing vegetation and wildlife when we are onsite. We will get information on general native and invasive species by looking into Chelsea Creek restoration and habitat conservation projects. In addition, the Massachusetts Department of Environmental Protection (MADEP) has a list of common native species used in environmental restoration projects. When onsite, we will also make sure to take pictures of the adjacent lands to the project area. Later in the design process, we will consider how the living shoreline will tie into adjacent lands and the possible negative consequences if the living shoreline fails. We will use failures from similar living shoreline types in the area to assist with analyzing end effects. Constructability is largely dependent on other site design factors like tide range, water depth, distance from shore, slope, site access, and permitting requirements. We will keep in mind that generally upland construction is the most cost effective. Project monitoring will be an important factor when choosing between living shoreline design alternatives. Creating a summary of maintenance time and cost from different literature for each living shoreline type will be helpful in the latter stages of this project.

3.4 Objective 3: Create Multiple Design Alternatives for Coastal Stabilization

After identifying the key characteristics of the site and projecting future conditions, we will begin creating and comparing multiple design solutions for coastal stabilization.

First, the qualitative and quantitative data from objective 2 will be placed into a rough suitability index established by Woods Hole Group (Woods Hole Group, 2017). This Excel-based tool provides a series of pull-down options that can be used to characterize a site's existing conditions. These pull-down options include energy state, existing environmental resources, nearby sensitive resources, tidal range, elevation, intertidal slope, bathymetric slope, and erosion. Based on the requirements of each type of living shoreline, the tool scores each living shoreline as “likely”, “possible”, or “unlikely” for that site. This suitability index will serve as a foundation on which a more focused design process can begin.

The next step is to establish quantitative value ranges for the design factor data collected in objective 2. This is the beginning of creating a more comprehensive version of the Woods Hole Group suitability index, as our tool will include all of the design factors analyzed in objective 2. These data ranges will be created based on the information gathered in the literature review of objective 1. For example, Stevens Institute of Technology has information we can use on living shoreline suitability for sites based on quantitative data. Different ranges will be created for low, moderate, and high existing conditions.

After the ranges are established, different scores will be allocated to each low, moderate, and high condition based on the type of living shoreline alternative. Deciding on which living shoreline alternatives should be scored will be based on both the results from the Woods Hole rough suitability index and a detailed analysis of the local case studies presented in the literature review. Factor scores will be weighted accordingly based on their importance to general living shoreline design. For instance, relative sea level will be weighted more heavily than sunlight exposure. Once the scoring system is finalized, the compatibility of each broad living shoreline design alternative will be evaluated by analyzing the scores. Higher scores denote a more suitable alternative, while lower scores denote a less suitable alternative. It should be noted that the design alternatives scored at this stage are discrete, meaning that combinations of different alternatives fitting together into one design have not yet been considered.

Once all of the individual living shoreline design alternatives have been scored, the results will be used to create several multi-faceted design solutions. As is often the case with living shoreline design, this project site will likely require a final design that combines multiple living shoreline approaches. For example, and this is only for illustrative purposes, reef balls may be needed in one area and a marsh sill in another. These multi-faceted solutions will be created based solely on the system's effectiveness for flooding mitigation and erosion control.

A cost comparison will be conducted between the multi-faceted design solutions determined in the previous step. The final results of the analysis will be in units of price per linear foot of shoreline. In order to reach this value, material, installation, and maintenance costs will be considered, along with a review of existing literature on living shoreline costs. Living shoreline cost data can be found in publications by The Mississippi Department of Marine Resources, The New Jersey Nature Conservancy, and a number of other private entities.

3.5 Objective 4: Identify a Final Design and Analyze Regulatory and Sustainability Implications

After creating multiple living shoreline solutions in objective 3, a final design will then be chosen based on the system's effectiveness and cost. Once a final living shoreline is selected, a more detailed and holistic design process will ensue.

Several shop drawings will be created using AutoCAD detailing material types, locations, planting arrangements, site grades and elevations, and surrounding infrastructure and ecological resources. Planting arrangements will largely be determined by the levels of hydrodynamic energy across the site. Regulatory, permitting, and legal barriers will be explored from the federal, state, and local levels. To begin this analysis, we will first use summaries of guidelines for living shoreline permitting processes, which can be found from sources such as the NOAA or the Virginia Institute of Marine Science. Relevant regulatory barriers will be identified according to the permitting boundaries of the site, which we will have previously mapped in GIS. We will create a list of the key permits needed to implement this project, including any permits unique to the City of Chelsea or the Greater Boston Area. Regional and federal environmental mandates and programs will also be identified. All of this data will be synthesized into a grading of feasibility and the creation of a timeline for the permitting process for a living shoreline design on the Chelsea Street Bridge parcel.

An estimate of the time for the living shoreline's development to become self-sustaining and the maintenance required over the living shoreline's lifetime will be provided. Maintenance costs such as fertilizer, replanting, addition of fill, and debris removal will be considered. The final design's sustainability and potential impacts, both positive and negative, on the surrounding environment will be analyzed. Using projected sea level rise and flooding data, an approximation of the system's longevity will be concluded. The compatibility of the plant species used in the living shoreline and species in adjacent lands will be investigated. Negative implications of the final design will be explored thoroughly by applying knowledge gained from a literature review of case studies to specific site conditions. Potential living shoreline co-benefits, like carbon sequestration, will be identified as well.

3.6 Project Schedule and Final Deliverables

The major deliverables of this project that will be presented to the City of Chelsea and submitted to Worcester Polytechnic Institute are as follows:

1) Literature review and project recommendations/methodologies
2) Recommendations for living shoreline alternatives
3) Shop drawings for final living shoreline design
4) Permitting memorandum detailing feasibility and timeline
5) Final written report

These deliverables are listed in order of estimated completion date, but are not expected to be completed in a linear fashion. A detailed schedule can be seen below to get a sense of the project timeline (Figure 9). The framework of the schedule consists of the four main project objectives and the deliverables. The objectives are further broken down into groups of similar tasks. It should be noted that this schedule contains rough dates and is subject to change throughout the project.

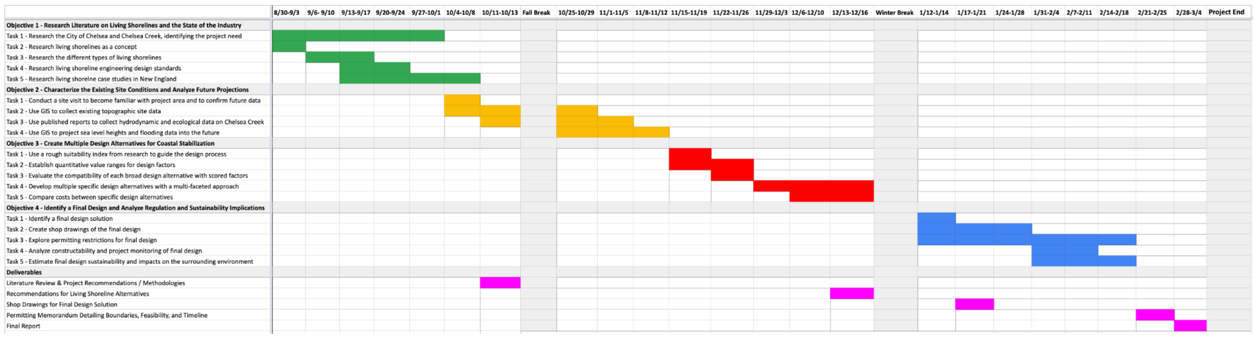

Figure 13: Project Gantt Chart.

4.0 Conclusion

The City of Chelsea is at high risk of flooding due to its low elevations relative to sea level, high groundwater tables, poorly draining soils, and lack of stormwater management infrastructure. The areas most susceptible to flooding include low income housing and industrial petroleum and salt operations. In order to be effective in the long term against the effects of climate change, coastal stabilization solutions must be dynamic with the rapidly changing environment. Living shorelines provide an environmentally beneficial alternative to traditional hard stabilization methods, as they have the ability to rise with the sea level, increase biodiversity, improve water quality, and serve as a carbon sequestration tool. This project focuses on mitigating erosion and flooding for a parcel of land along Chelsea Creek next to the Chelsea Street Bridge. Our project seeks to identify a comprehensive final living shoreline design from a list of generated design alternatives. Regulations and permitting, constructability, maintenance, impacts on the surrounding environment, and co-benefits will be explored for the final design. This research can be used by the City of Chelsea to aid in their process of developing a flooding mitigation plan and increasing public waterfront access along Chelsea Creek.

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Appendix B: Authorship Table

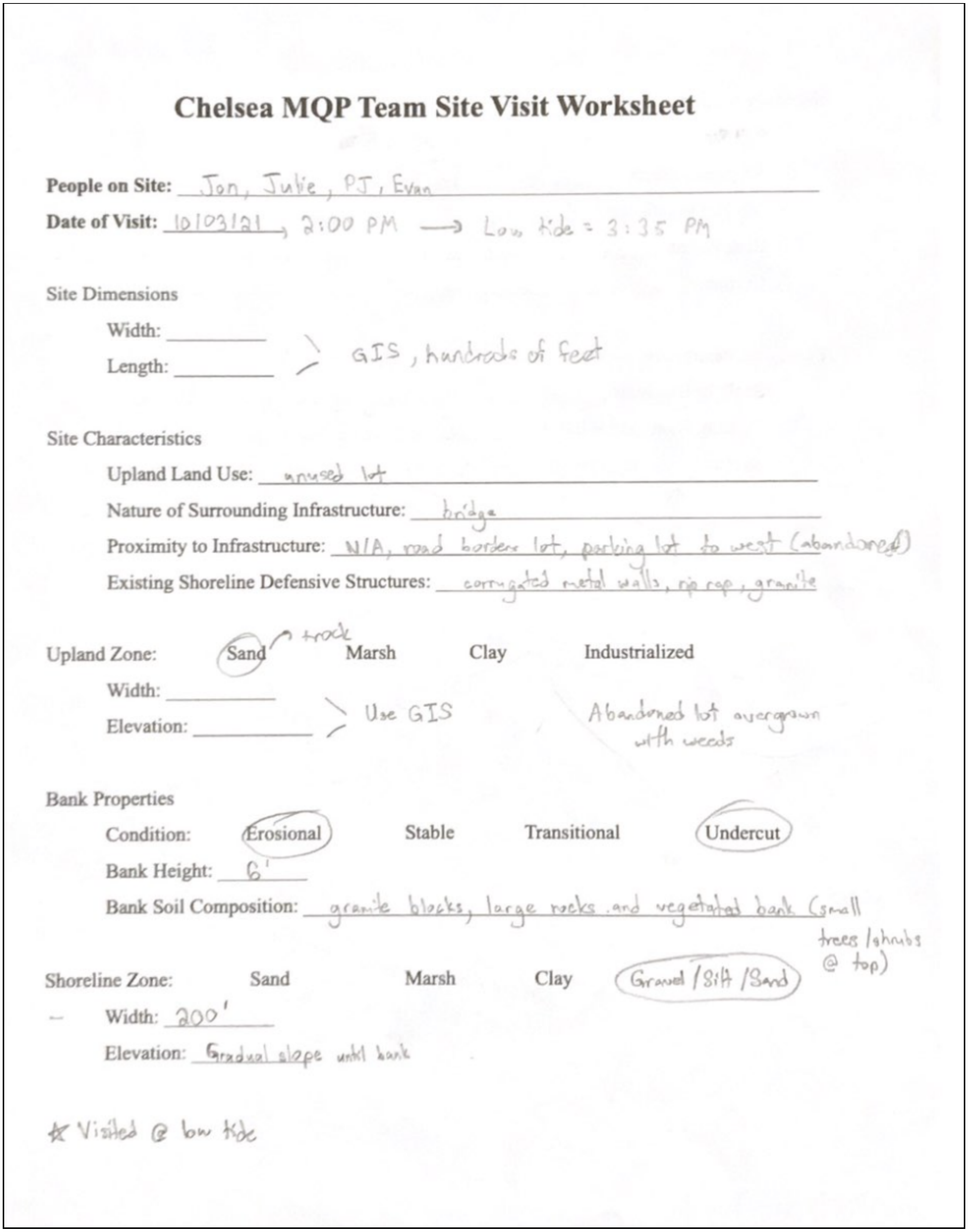
REPORT SECTION	AUTHOR(S)	EDITOR(S)
Executive Summary	Jonathan	Evan
1.0 Introduction	Evan, Jonathan	Peter
2.0 Background	-	-
2.1 Global Warming and Sea Level Rise	Evan	Julie
2.2 Background on the City of Chelsea	Julie, Evan	Peter
2.2.1 The History of the City of Chelsea	Julie	Evan
2.2.2 The City of Chelsea's Demographics	Julie	Jonathan
2.2.3 General Information on Chelsea Creek	Evan	Julie
2.3 What is a Living Shoreline?	Jonathan	Julie
2.4 Living Shorelines vs. Structural Shorelines	Evan, Jonathan	Julie
2.5 Engineering Guidelines for Living Shoreline Design	Jonathan	Peter
2.6 Living Shoreline Permitting Process	Peter	Jonathan
2.7 Living Shoreline Case Studies in New England	Peter	Evan
3.0 Methodology	-	-
3.1 Introduction	Jonathan	Peter
3.2 Objective 1: Research Literature on Living Shorelines and the State of the Industry	Jonathan, Julie	Peter
3.3 Objective 2: Characterize the Existing Site Conditions and Analyze Future Projections	Evan, Jonathan, Julie	Peter
3.4 Objective 3: Create Multiple Design Alternatives for Coastal Stabilization	Evan	Jonathan, Julie
3.5 Objective 4: Identify a Final Design and Analyze Regulatory and Sustainability Implications	Peter	Evan/Julie
3.6 Project Schedule and Final Deliverables	Jonathan	Julie
4.0 Results	-	-

4.1 General Existing Site Conditions	-	-
4.1.1 Site Visit	Evan	Jonathan
4.1.2 Site Mapping	Jonathan	Peter
4.2 Living Shoreline Sustainability	-	-
4.2.1 Collecting Site Data on Living Shoreline Design Parameters	Jonathan	Julie, Evan
4.2.2 Living Shoreline Site Suitability Matrix	Jonathan	Julie, Peter
4.3 Cost Analysis and Estimates	Evan	Jonathan
4.4 Comparing Cost Versus Suitability	Peter	Julie
4.5 Possible Design Combinations	Peter	Evan
5.0 Recommendations	-	-
5.1 Final Design Combination	Julie	Evan, Jonathan
5.1.1 Presentation of Final Design	Jonathan	Peter
5.1.2 Explanation of Final Design	Peter	Jonathan, Julie
5.2 Implementation Strategy	Jonathan	Evan
5.3 Permitting Memorandum	Jonathan	Julie
6.0 Limitations	-	-
Data Collection Limitations	Julie	Jonathan
Cost Analysis Limitations	Evan	Jonathan
Sustainability Considerations Limitations	Jonathan	Julie
7.0 Conclusion	Evan, Peter	Jonathan
Appendix C: Detailed Site Visit Information	Evan	Jonathan
Appendix F: Permitting Sources	Jonathan	Peter

Appendix C: Detailed Site Visit Information

The site visit occurred on October 3, 2021 at 2:00 PM. Low tide that day was at 3:35 PM. Measurements of the site were obtained via an open reel tape measure. The October 3, 2021 site visit worksheet can be seen below in Figures 45 and 46.

The team first arrived at the site from the west. On the site, there was a small beach area with existing rip rap, a corrugated metal breakwater about 30 feet offshore, and a granite retaining wall all to the west of the beach. The beach begins to gradually narrow and taper off to the east. To gain a sense of square footage, the team measured the dimensions of the beach, which was about 100 feet by 52 feet for the main portion of the beach that was to the west of the bridge. Under the bridge, the beach narrowed to 35 feet in width and eventually as narrow as 9 feet. This section was 100 feet in length as well.



Chelsea MQP Team Site Visit Worksheet

People on Site: Jon, Julie, PJ, Evan

Date of Visit: 10/03/21, 2:00 PM → Low tide = 3:35 PM

Site Dimensions

Width: ______ } GIS, hundreds of feet

Length: ______

Site Characteristics

Upland Land Use: unused lot

Nature of Surrounding Infrastructure: bridge

Proximity to Infrastructure: N/A, road border lot, parking lot to west (abandoned)

Existing Shoreline Defensive Structures: corrugated metal walls, rip rap, granite

Upland Zone: (Sand) ↗ track Marsh Clay Industrialized

Width: ______ } Use GIS

Elevation: ______

Abandoned lot overgrown with weeds

Bank Properties

Condition: (Erosional) Stable Transitional (Undercut)

Bank Height: 6'

Bank Soil Composition: granite blocks, large rocks, and vegetated bank (small trees/shrubs @ top)

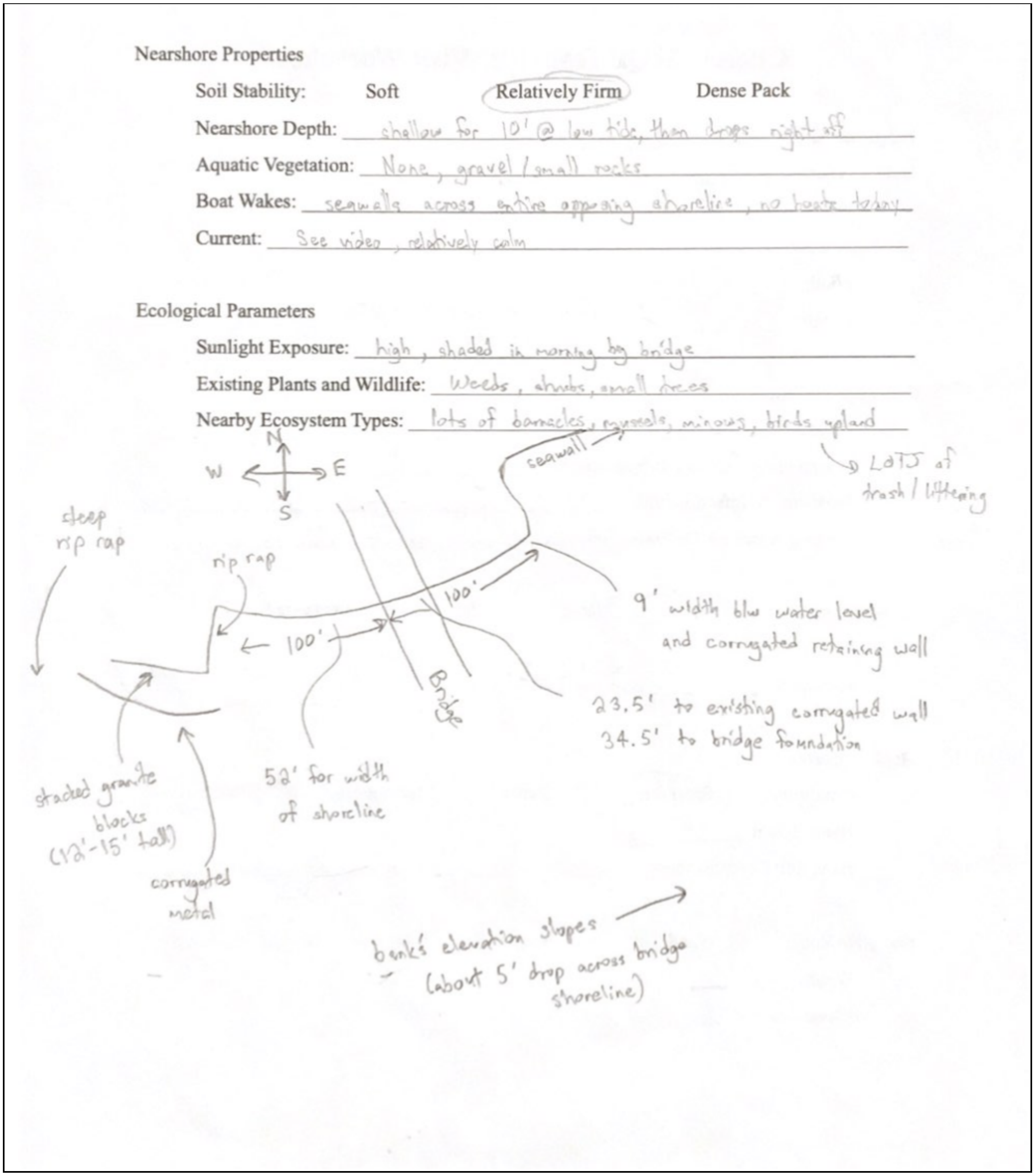
Shoreline Zone: Sand Marsh Clay (Gravel/Silt/Sand)

Width: 200'

Elevation: Gradual slope until bank

☆ Visited @ low tide

Figure 45: Front Page of 10/03/21 Site Visit Worksheet.



Nearshore Properties

Soil Stability: Soft Relatively Firm Dense Pack

Nearshore Depth: shallow for 10' @ low tide, then drops right off

Aquatic Vegetation: None, gravel / small rocks

Boat Wakes: seawalls across entire opposing shoreline, no boats today

Current: See video, relatively calm

Ecological Parameters

Sunlight Exposure: high, shaded in morning by bridge

Existing Plants and Wildlife: Weeds, shrubs, small trees

Nearby Ecosystem Types: lots of barnacles, mussels, minnows, birds upland

Figure 46: Back Page of 10/03/21 Site Visit Worksheet.

Appendix D: Parcel Map

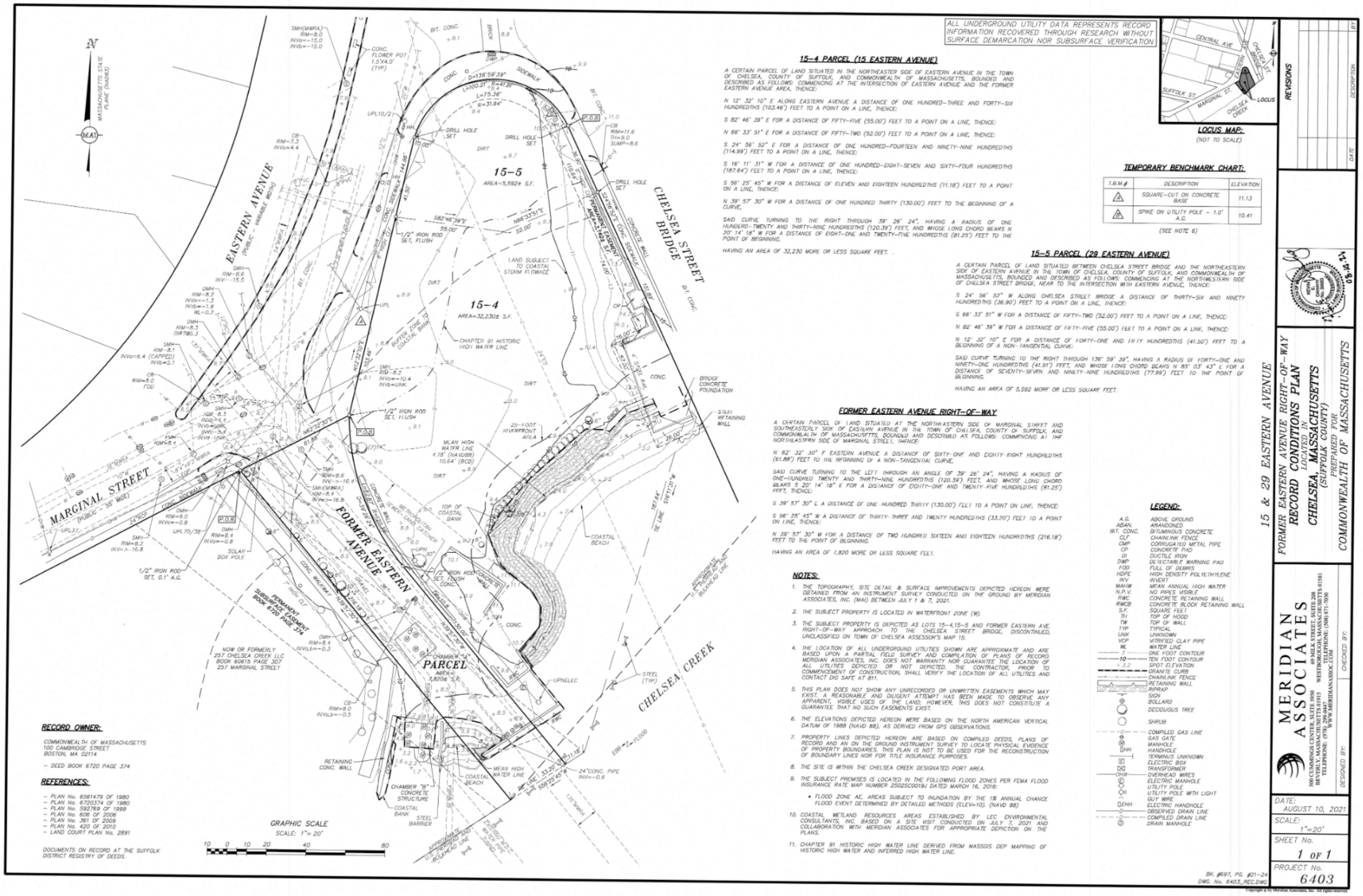


Figure 47: Parcel map from Meridian Associates in August of 2021. (Meridian Associates, 2021)

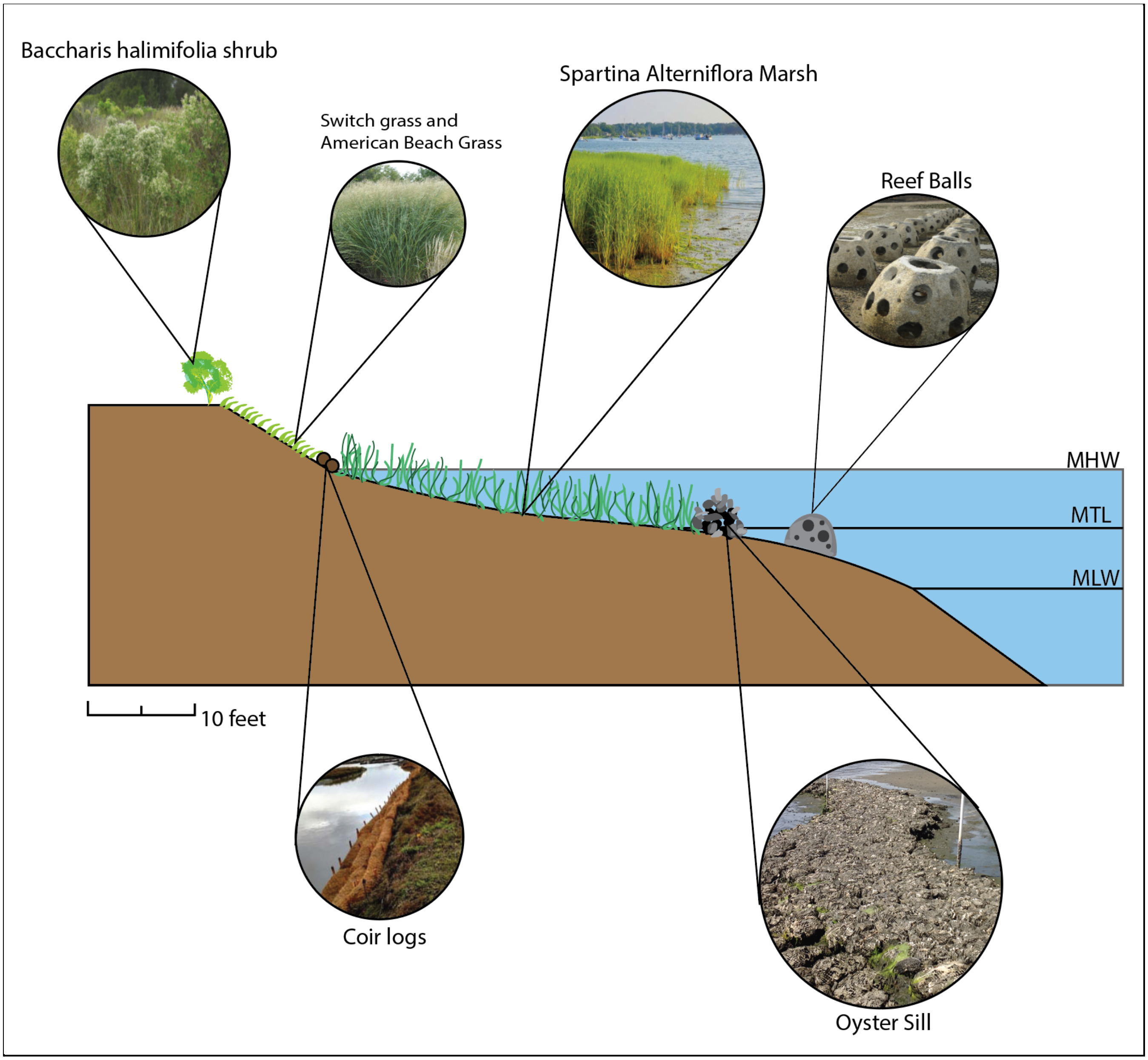
Appendix E: Design Elements Infographics

Improving Long-Term Coastal Resiliency: A Living Shoreline Design for Chelsea Creek

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

Evan Andrzejewski, Peter Conroy, Julie Pham, Jonathan Scribner

March 2022


Baccharis halimifolia shrub
Switch grass and
American Beach Grass
Spartina Alterniflora Marsh
Reef Balls
MHW
MTL
MLW
10 feet
Coir logs
Oyster Sill

American Beachgrass

(Ammophila Arenaria)

Function: Bank Stabilization and Erosion Control

Dimensions & Provisions

*Location: Upland bank

*2-3' tall, 18" spacing

*roots can grow up to 8' deep

*plant two 18-24" stems in a hole approximately 7-9" deep

Advantages

*Quickly establishes dense root system

*Very tolerant of severe maritime exposure

*Useful as initial erosion control plant

Cost & Maintenance

*$0.20 each plant

*Requires fertilizing

Project: Development of a Living Shorline for the City of Chelsea, MA

Sources: (Miller, n.d.)
(Massachusetts Office of Coastal Zone Management, 2018)
(Sea Grant New York, n.d.)

Reef Balls

(Bay Ball Mold)

Function: Living breakwater

Advantages

* Micro silica concrete has pH similar to seawater and lasts for 500 years

* Easy to deploy

* Great for shallow water

Dimensions & Provisions

* 3 ft base diameter, 2 ft tall

* Weighs about 500 lbs

* 14 interconnecting holes

* Aggregate exposed outside surface texture

* Anchoring provided by 3-4 pieces of battered #5 fiberglass rebar driven into the seabed

Cost & Maintenance

* $130 each ball

* No significant maintenance

Project: Development of a Living Shorline for the City of Chelsea, MA

Sources: (Reef Ball Brochure & Key Features Page, n.d.)
(Molds, Suggested Retail Prices & Training/Consulting Services Pricing, n.d.)

Coir Logs

(Coconut Fiber)

Function: Bank Toe Stabilization and Erosion Control

Advantages

*Protects the toe of the bank

*Helps with erosion control

*Can be planted on

Dimensions & Provisions

*Location: Bank Toe

*1' dia., 10' long, 9 pcf (natural net)

*Hardwood stakes staggered 2' on center on each side

*Rope lashing

* 2 rows across 100 feet, 20 rolls total

Cost & Maintenance

*$110 each roll

*$750 maintenance every year for the first 5 years

Project: Development of a Living Shorline for the City of Chelsea, MA

Sources: (CocoLogix Bank Stabilization Systems, 2020)

Erosion Control Blanket

(ECC-2B Compressed Coconut Net)

Function: Planting Base and Erosion Control

Dimensions & Provisions

* "ECC-2B"

*Uniformly distributed 100% coconut fiber and two organic jute nets securely sewn together with biodegradable thread

Advantages

* Biodegradable

*Suitable for slopes 1:1 and medium to high flow channels

Cost & Maintenance

*$250 per 4'x225' blanket

*Inspect every 2-3 months for first year for good blanket-soil contact

Project: Development of a Living Shorline for the City of Chelsea, MA

Sources: (East Gate Supply, n.d.)
(Newp, n.d.)

Salt Marsh

Smooth Cordgrass (Spartina Alterniflora)

Function: Shoreline stabilization and wave dissipation

Dimensions & Provisions

* Less than 40 inches tall when fully grown

* 1 ft planting spacing

* Plant 6-8 inches deep in soil

Advantages

* 32 Species of Greatest Conservation Need that depend on salt marshes

*Improve water quality and carbon sequestration

* Dissipate wave energy

Cost & Maintenance

* $1.50 each plant

* Fertilizer is optional, but not vital

Project: Development of a Living Shorline for the City of Chelsea, MA

Sources: (Materne, 2000)

Oyster Sill

Atlantic Oyster (Crassostrea Virginica)

Function: Living breakwater and marsh toe support

Dimensions & Provisions	Advantages	Cost & Maintenance
* Each bag is 3 ft wide and 1.5 ft tall	* Increase biodiversity due to richness in calcium carbonate	* $40 per cubic yard
* 2 bags placed next to each other, 2 bags high	* Improve water quality	* Inspections to ensure oysters are not buried in the soil

Project: Development of a Living Shorline for the City of Chelsea, MA

Sources: (Milligan et al., 2018)

Saltbush

(Baccharis halimifolia)

Function: Soil Stabilization and Stormwater Control

Dimensions & Provisions

* 8'-12' tall

*6'-12' wide

*5' spacing

Advantages

*High salinity tolerance

*Native to MA

*Not affected by diseases or pests

*Wide soil type tolerance

Cost & Maintenance

*$9.50 per plant

*Mowing and broadleaf herbicide treatments in 1-3 year intervals to control growth

Project: Development of a Living Shorline for the City of Chelsea, MA

Sources: (Van Deelen & Timothy, 1991)
(New P, n.d.)

Switchgrass

(Panicum Virgatum)

Function: Bank Stabilization and Erosion Control

Advantages

* Can stabilize exposed areas quickly with fast-growing, fibrous root systems

* Wide soil type tolerance

* Host for birds/wildlife

Cost & Maintenance

* $4.00 each plant

* Fertilizer not effective and not needed

Dimensions & Provisions

* 3-6 ft tall when fully grown

* 2 ft planting spacing

* Roots can grow up to 6 ft deep within soil

Project: Development of a Living Shorline for the City of Chelsea, MA

Sources:(Prairie Nursery, n.d)
(Gardenia, n.d.)
(Carter, 2011)

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Appendix F: Permitting Sources for Future Work

Numerous online resources were used to complete the permitting analysis in this project. This appendix lists key sources that the City of Chelsea can reference in future work. The sources are separated between the state and federal permitting processes.

State Permitting Useful Sources

Massachusetts General Laws Chapter 91 Text:
https://malegislature.gov/Laws/GeneralLaws/PartI/TitleXIV/Chapter91

Clean Water Act Section 401 Overview and 2019 Changes:
https://www.epa.gov/sites/default/files/2020-06/documents/overview_fact_sheet_for_the_clean_water_act_section_401_certification_rule.pdf

Clean Water Act Section 401 Text from EPA:
https://www.epa.gov/cwa-401/clean-water-act-section-401-state-certification-water-quality

Massachusetts Environmental Policy Act Regulations Review Thresholds:
https://www.mass.gov/regulations/301-CMR-1100-mepa-regulations#11-03-review-thresholds

Massachusetts Office of Coastal Zone Management 2011 Policy Guide:
https://www.mass.gov/files/documents/2016/08/qc/czm-policy-guide-october2011.pdf

Wetlands Protection Act (MGL c. 131, s. 40) Text:
https://malegislature.gov/Laws/GeneralLaws/PartI/TitleXIX/Chapter131/Section40

DEP 310 CMR 10.00: Wetlands Protection:
https://www.mass.gov/doc/310-cmr-1000-the-wetlands-protection-act/download

Federal Permitting Useful Sources

Nationwide Permit 54 - Living Shorelines:

https://www.swt.usace.army.mil/Portals/41/docs/missions/regulatory/NationwidePermits/Nationwide%20Permit%2054%20-%20Living%20Shorelines.pdf?ver=2017-03-31-150711-473

U.S. Army Corps of Engineers Permitting Process Information:
https://www.lrl.usace.army.mil/Portals/64/docs/regulatory/Permitting/PermittingProcessInformation.pdf

Department of the Army General Permits for the Commonwealth of Massachusetts:
https://www.nae.usace.army.mil/Portals/74/docs/regulatory/StateGeneralPermits/MA/PN-GPFinal-RevApril2018.pdf?ver=2018-07-31-142949-100

ENG Form 4345:
https://www.publications.usace.army.mil/Portals/76/Publications/EngineerForms/Eng_Form_4345_2018May.pdf