Climate Change Adaptation Strategies for Coastal Military Installations:

Design and Planning Principles for Naval Facilities Engineering Command

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Abstract

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Climate change has become a major focus of the Department of Defense (DOD), and each service is required to look at adaptation from an operational and logistical perspective. Resiliency within installations in the United States is imperative in order to preserve operational readiness and shore security. This thesis explores climate change, related effects, and sea level rise projections within the United States. The Department of Navy (DON) is the primary service of focus, since the U.S. Navy is the primary service along our coasts and our guardian of the seas. The thesis transitions into the major qualitative section, in which three primary adaptive design principles**-** *Protect*, *Adapt*, *or Retreat* are examined. Each principle is reviewed for the technical benefits and concerns of the system, as well as cost, time, maintenance, environmental impacts, and built robustness factors that influence military operational and physical readiness. The thesis also demonstrates that the best design or planning strategy may include a combination of the adaptation strategies. The thesis transitions into an evaluation framework that is comprised of: first presenting how to conduct an installation risk and vulnerability assessment, second the demonstration of the design and planning evaluation framework, and lastly how can design or planning strategies be implemented into action. In conclusion, the thesis demonstrates how the evaluation framework can be used by Naval Facilities Engineering Command (NAVFAC) to guide policy and funding decisions.

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ABBREVIATIONS

ADA-Americans with Disabilities Act

ASCE- American Society of Civil Engineers

AR4- IPCC Fourth Assessment Report

BFE- Base Flood Elevation

CBA- Capabilities Based Assessment

CIP- Capital Improvements Plans

CNIC- Commander Navy Installation Command

DPG- Defense Programming Guidance

DFE- Design Flood Elevation

DSCA- Defense Support to Civil Authorities

DOD- Department of Defense

DON-Department of Navy

EBM- Ecosystem-Based Management

EI&E- Office of the Assistant Secretary of Defense Energy, Installations, and Environment

EWL- Extreme Water Level

EXWC- Engineering and Expeditionary Warfare Center

FEC- Facilities Engineering Command

FIRMS-Flood Insurance Rate Maps

FY-Fiscal Year

FT- Feet

GHG-Green House Gas

HFC- Hydrofluorocarbon

ICO- Installation Commanding Officer

IPCC- Intergovernmental Panel on Climate Change

MAP- Maintenance Action Plan

MEP- Maintenance Execution Plan

MILCON-Military Construction

NAVD- North American Vertical Datum

NAVFAC- Naval Facilities Engineering Command

NGVD- National Geodetic Vertical Datum

NSP-Navy Strategic Plan

POM- Program Objective Memorandum

QDR- Quadrennial Defense Review

SECNAV-Secretary of the Navy

SFHA-Special Flood Hazard Area

SLR- Sea Level Rise

SPP- Sponsor Program Proposals

SRM- Sustainment, Restoration, and Maintenance

1. INTRODUCTION

1.1 Context

Climate Change and the United States' ability to adapt and increase resiliency to its secondary effects is critical not only for the environmental, economic, and quality of life perspective of its citizens, but will also be an increasingly significant factor in the ability to maintain national security at home and abroad (Barnett 2001). The Department of Defense (DOD) tasked with managing our national defense through the coordinated operations of the United States Armed Forces[1], has in accordance with the direction in Executive Order 13653, issued and established policy which assigns responsibilities to provide the DOD with the resources necessary to assess and manage risks associated with the impacts of climate change (DOD 2016). Climate Change will affect how the military is able to conduct its missions operationally and could increase the frequency and scope of how military forces will need to support humanitarian crisis and civil conflict abroad (DOD 2014a). Operational readiness is directly linked to the planning, preparation, and support services that are provided through military installations. This thesis specifically focuses on coastal installations, and how they are specifically vulnerable to sea level rise, and storm surge, and flooding events.

The United States Navy's mission is to maintain, train, and equip combat-ready naval forces capable of winning wars, deterring aggression and maintaining freedom of the seas (DON 2016). As the primary force to safeguard our seas, United States naval operations and installations are specifically vulnerable to sea level rise, flooding, and storm surge events. Recent studies have shown that the overwhelming bulk of humanity is concentrated along or near coasts on just 10% of the earth's land surface. As of 1998, over half the population of the planet — about 3.2 billion people — lives and works in a coastal strip just 200 kilometers wide (120 miles), while a full two-thirds (4 billion), are found within 400 kilometers of a coast (Hinrichsen 1999). With an escalation of population, climate change, and instability due to strained resources, the DON will increasingly be tasked to safeguard our seas, assist in

[1] United States Armed Forces includes the five armed service branches: Air Force, Army, Coast Guard, Marine Corps, and Navy.

humanitarian crisis abroad, and engage in coastal civil unrest. Operational readiness for the DON in a changing climate will be closely linked to the resiliency of the built infrastructure ashore, and its ability to withstand climate change and specifically the threat of sea level rise, storm surge, and coastal flooding.

1.1.1 Climate Change

Climate change is occurring on a global scale, and is manifesting itself differently region to region. No nation will be immune to the impacts of climate change. However, the distribution of impacts is likely to be inherently unequal and tilted against many of the world's poorest regions, which have the least economic, institutional, scientific, and technical capacity to cope and adapt (The World Bank 2012). There is one indisputable fact that supports climate change, the Earth's atmosphere has a carbon dioxide concentration higher than it has been in at least 800,000 years, and the concern is not only the concentration, but the rate at which concentrations occurred since the modern industrial revolution. The rapid increase of carbon dioxide can be attributed to human activities that produce greenhouse gases, and thus result in an overall warming of the Earth's temperature (Brown and Sovacool, 2011, Rosenzweig et al. 2011). On a global scale, the key indicators of climate change include:

1. Global warming
2. Sea Level Rise
3. Intensification of tropical cyclones
4. Decreases in meridional overturnings of the Atlantic Ocean
5. Declining ocean PH (ocean acidification)
6. Decreasing snow cover, permafrost, and sea ice
7. More frequent and more intense extreme weather events
8. Increasing rainfall in high latitudes and decreasing rainfall in the subtropics
9. Changing micro-climates that will affect food production

On a global scale all of these trends are occurring, it is important to remember that although we may not experience some of these threats locally, holistically on a global level the impacts are combined (IPCC 2014, Rosenzweig et al. 2011).

From baseline global mean temperatures measured between 1986-2005 the projected global temperature increase by year 2100, ranges between 2-6 degrees Celsius, with the highest concentration of heat centered around the Arctic. Rising Arctic temperatures will perpetuate further glacier and sea ice melting, this along with rising sea temperatures, which cause ocean volumes to swell, will directly contribute to sea level rise (IPCC 2014). The world community lead by the Intergovernmental Panel on Climate Change (IPCC) has concluded that a two-pronged response is required, the world must mitigate and change practices that contribute to greenhouse gas emissions, and secondly we must adapt. Climate change has already been put into action, although mitigation practices can slow additional CO2 emissions, adaptation programs must also be initiated to proactively address the unavoidable effects of climate change (IPCC 2014).

1.1.2 Climate Change and Instability in the World

There is growing concern throughout the world of violent conflict, and that this conflict will continue to grow in direct correlation to climate change and its impacts. It is not climate change, for example higher temperatures that directly causes conflict, but instead the social, economic, and resource instability that is exacerbated by climate change (Barnett 2001, Busby 2007, DOD 2010). Feelings of unrest, fear, and inequality occur, when tension related to changing terms of trade, resource scarcity, reductions in freshwater and food availability, exposure to new diseases, and the introduction of mass numbers of new people due to migration occur. When people are upset with their social standing, and fearful of their future, they are more likely to act out in desperate manners. Former Secretary of Defense, Chuck Hagel[2] stated- "the challenge of global climate change, while not new to history, is new to the modern world.

[2] Chuck Hagel served as Secretary of Defense from February 27, 2013 – February 17, 2015.

Climate change does not directly cause conflict, but it can significantly add to the challenges of global instability, hunger, poverty, and conflict. Food and water shortages, pandemic disease, disputes over refugees and resources, more severe natural disasters – all place additional burdens on economies, societies, and institutions around the world" (DOD 2014a).

Developed countries have the means and social structure to mitigate and adapt to climate change, while developing countries do not often have the political and economic resources to change. Align this with the trend that major powers (typically developed countries) are more likely to be involved with international conflict as they seek to curb violence at home and/or abroad. Less developed countries do not have the political and military power often to curb unrest before it becomes rampant within their borders (Barnett 2001, Busby 2007).

1.1.3 Department of Defense Climate Change Initiatives

Climate Change will have major impacts to United States security both domestically and abroad. Domestically our coastlines are vulnerable to rising sea level, flooding, and damages due to major climate events (hurricanes). Nearly 40% percent of Americans live within counties along our coasts (NOAA 2016), billions of dollars' worth of infrastructure is along the coast, and key military bases are located along the coast (NAS 2011). Internationally millions of people are vulnerable to living near the coastline (10% of world population), drought, increased flooding, and food/water scarcity (Harris et al. 2014). The United States cares about these environmental and humanitarian crises, because of the spillover effects that cause major conflict in developing areas around the world. History has repeatedly shown that where there is conflict, desperate people, and an instable government, violent and terrorist groups can easily move in and exacerbate the situation.

The DOD has established three broad adaptation goals that are defined in the *2014 DOD Climate Change Adaptation Road Map*:

Goal 1: Identify and assess the effects of climate change on the Department.

Goal 2: Integrate climate change considerations across the Department and manage associated risks.

Goal 3: Collaborate with internal and external stakeholders on climate change challenges.

These goals are then divide into four areas of effort, which each service must translate into achievable actions: Plans and Operations, Training and Testing, Built and Natural Infrastructure, and Acquisition and Supply Chain (DOD 2014a). For the purpose of this thesis, built and natural Infrastructure are the lens of focus[3].

1.1.4 Department of Navy Risk Operationally and Logistically

The United States Navy has placed a priority on climate change and the operational risks. The *2010 United States Navy Climate Change Roadmap* discusses the operational threat, and assigns responsibly to individual commands on their involvement with combating and adapting for climate change. Specifically related to infrastructure and installation resilience, the document assigns responsibility to NAVFAC in addressing sea level rise impacts on infrastructure and real estate. NAVFAC through strategic investments must develop and implement infrastructure adaptation strategies, including strategies for water resource challenges, and strategies that consider impact of climate change on future missions and force structure (DON 2010). NAVFAC has taken very aggressive measures to mitigate climate change, including reduction of facility energy usage by 30% by 2015 and 50% by 2020 (as compared to a fiscal year 2003 baseline), and has set policy to produce or procure 50% of facility energy requirements from

[3] Built and Natural Infrastructure includes facilities, ports, roads, utility systems, as well as the shoreline and nature based ecosystems.

alternative sources by 2020 (CNIC 2014). Although the Navy is lagging slightly in facility energy savings (19.0% through 2013 vs. goal of 24%), the sea service now satisfies 26.6% of facility energy needs from renewable sources, more than halfway to their 50% goal (DOD 2014b).

Although the DON through NAVFAC has made significant strides in the mitigation front against climate change and carbon emissions, it still lacks a comprehensive adaptation guidance document to detail policy from a shore installation and facility perspective. Focus has been placed on gathering data on current science of climate change and specifically sea level rise projections for each installation, which has been captured in the DoD Sea Level Rise (SLR) and Extreme Water Level (EWL) Scenario database website first published in August 2016[4]. In addition, NAVFAC is currently reviewing a number of its building codes and standards dictated through the Unified Facilities Code as related to climate change and specifically sea level rise. There is a major gap thought between the sea level rise projections developed, and the resulting design, building code, and planning implications. A guidance document explaining the range of adaptation responses is critically needed to direct planning and investment decisions.

1.2 Research Question

The purpose of this thesis is to demonstrate how coastal military facilities engineers can increase resiliency on military installations throughout the United States, by applying a set of adaptive design and planning principles within an evaluation framework, to best adapt to climate change and sea level rise. Coastal military facilities engineers should be able to first understand the cause and effects of sea level rise and climate change as applied to their environment. They shall understand that through proactive planning and adaptation now, they can significantly increase resilience for shorelines and coastal

[4] The DoD Sea Level Rise (SLR) and Extreme Water Level (EWL) Scenario database website is available for all DOD installations. The tool provides localized information on future SLR and EWL for three time horizons to assist with climate change adaptation planning for DOD coastal and tidally influenced sites worldwide. These scenarios provide a decision-maker with temporal and physically-based information to assess future vulnerabilities. Although these scenarios are intended to be used in a "screening" context and not detailed engineering design, their development collectively represents several advancements in scenario development for coastal locations that can serve as a starting point for other applications (SERDP 2016).

infrastructure for the future, and through conducting a vulnerability analysis, they can effectively choose a design and planning strategy through the evaluation framework that will create resiliency. Resiliency in social-ecological systems has been defined as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker et al. 2004). Department of Homeland Security views resiliency in relation to infrastructure as the ability to resist, absorb, recover from, or successfully adapt to adversity or a change in conditions (DHS 2010).

Thesis Question- How can coastal military facilities engineers increase resiliency on military installations throughout the United States, by evaluating and applying a set of adaptation design and planning principles to best adapt to climate change as applied to: sea level rise, storm surge, and flooding.

Sub Questions-

1. With a number of competing interests and data available, what is the most effective method of analyzing and applying a planning or design strategy on each coastal military installation?
2. With limited funds how can adaptation planning and design strategies be implemented into capital improvement plan (CIP) and maintenance execution plans (MEP) incrementally, increasing resiliency steadily.

1.3 Intended Audience

The intended audience for this thesis is NAVFAC, and the associated Leadership, Public Works Officers, Assistant Public Works Officers, and Planning Staff. NAVFAC is the Systems Command that builds and maintains sustainable facilities, delivers utilities and services, and provides Navy expeditionary combat force capabilities. The goal is to provide a comprehensive design and planning evaluation framework, which allows NAVFAC leadership to best decide adaptive strategies against sea level rise and climate change within naval shore infrastructure and coastal property. Although the thesis is targeted to provide sound strategies for Naval Leadership, the principles and evaluation framework could also be adapted to coastal civilian planners and municipalities.

1.4 Research Design

This thesis' research methodology is inductive in nature and based in grounded theory. Qualitative data related to risk and adaptative strategies against climate change and sea level rise for coastal infrastructure are analyzed and critiqued, in order to produce an adaptation evaluation framework for military engineers and planners. Grounded theory is the research process that is derived from real-world situations, in which the researcher creates and evaluates theories derived from real-world settings, and those theories are thus applied in practice or test case settings. Grounded theory is not a prescribed method that uses a particular level of data and formulistic techniques to calculate a solution…Grounded theory is a way of thinking about data-process of conceptualization-of theorizing from data collected by interviewing and observing everyday life (Morse et al. 2009).

Data is comprised of the following sources-

Written- Review and analysis of peer reviewed journals and books that demonstrate scientific knowledge on climate change, U.S. military security policy related to climate change, and adaptive planning and design practices for coastal infrastructure/shorelines.

Interviews with NAVFAC personnel- Discussions occurred with NAVFAC personnel serving in leadership or planning roles to discuss current policies, initiatives, and challenges related to NAVFAC's approach to sea level rise, storm surge, or coastal flooding.

<u>Case Studies Demonstrating Best Practices</u>- Adaptation strategies classified under the strategies of *Protect, Accommodate or Retreat* are examined, demonstrating the benefits, concerns, cost, time, maintenance, and resiliency implications of each strategy. Visual examples and case studies will explore the technical merits of each adaptation strategy.

1.4.1 Purpose of Data

There are numerous studies and journals that discuss the science of climate change, and the IPCC creates reports that serve as strong basis for climate change data. The value of this data is to document that climate change and sea level rise are not static, and although infrastructure and shorelines may be performing sufficiently at their current state, the frequency of flooding, coastal storm surge, and sea level rise will only continue to cause greater risk. After review, there is a large amount of information available on adaptive design and planning strategies, most data sources discuss the strengths of their strategy, and occasionally critique other strategies, but there is no comprehensive comparison of all strategies as applied to a military context or how adaptative strategies could be used in combination. Several source have already stated that coastal planners often feel overwhelmed in the amount of information, and have difficulties choosing which strategy for their specific application with confidence (Langridge et al. 2014). The goal of this thesis is to streamline the decision process, and with thorough analysis concisely demonstrates the strengths and weaknesses of each adaptation strategy as related to *Protect, Accommodate, or Retreat* policy.

The thesis uses qualitative data to demonstrate grounded theory on:

- The science and effects of climate change and sea level rise.
- Why climate change is a threat to U.S. military operational security.
- The best planning and design strategies for a variety of coastal shorelines and infrastructure.
- How strategies be strategically chosen through a vulnerability assessment and evaluation framework for the best application.

1.5 Thesis Structure

The thesis is broken down into six primary categories: (1) Introduction of the thesis question and hypothesis, (2) a literature review on current climate change science, security threats, and spectrum of adaptation strategies, and (3) a methodological analysis of each adaptation strategy. The thesis then transitions to (4) a risk assessment, and planning and design evaluation framework to choose the most appropriate adaptation strategy, (5) discusses how adaptation strategies can be incorporated into DON policy, and (6) concludes on the value of additional research and application into practice.

1.5.1 Primary Deliverables

The primary deliverables that is of use to the intended audience are the Literature Review, Methodology, Results, and Discussion Chapters. These chapters apply all the knowledge gained from data collection, and provide a rational systematic process to assess vulnerability, evaluate the best planning and design strategy, and then create a plan on how to increase resiliency through existing tools and procedures already included in DON infrastructure planning.

Figure 1: Primary Deliverables

(Caponigro 2017)

Step 1

Vulnerability Assessment

- **Identify Critical Infrastructure**
- **Identify Essential Systems and Codependency**
- **Identify Sensitive Environmental Areas**
- **Who Provides and Depends on Services (Power, Water, Waste Water Treatment, Fire, Medical, and Security for example)**
- **Identify Natural, Technological or Man-Made Hazards and How are they Amplified By Climate Change**
- **Identify Base Infrastructure Within Sea Level Rise Projections**

Figure 1: Primary Deliverables (Continued)

Step 2

Evaluation Framework

- **Evaluate Installation Vulnerabilities Against Design and Planning Strategies**
  - **Protect**
  - **Accommodate**
  - **Retreat**
- **Compare-Benefits, Concerns, Cost, Time, Maintenance, and Resiliency**
- **Select Design or Planning Strategy**
  - **More than one option may apply**
  - **Different areas or pieces of infrastructure may require varying levels of resiliency**

Step 3

Implement into Action

- **Incorporate Into- NAVFAC Policy, Capital Improvement Plans, and Maintenance Execution Plans**
- **Publish-Adaptation Policy issued in Guidance.**
- **Prioritize-Funding Allotted Into Budget**
- **Identify Opportunities-Incorporate Strategy Into Existing Design/ Construction Projects or Incorporate Into Public Works Annual Maintenance Policies.**

2. LITERATURE REVIEW

2.1 Introduction

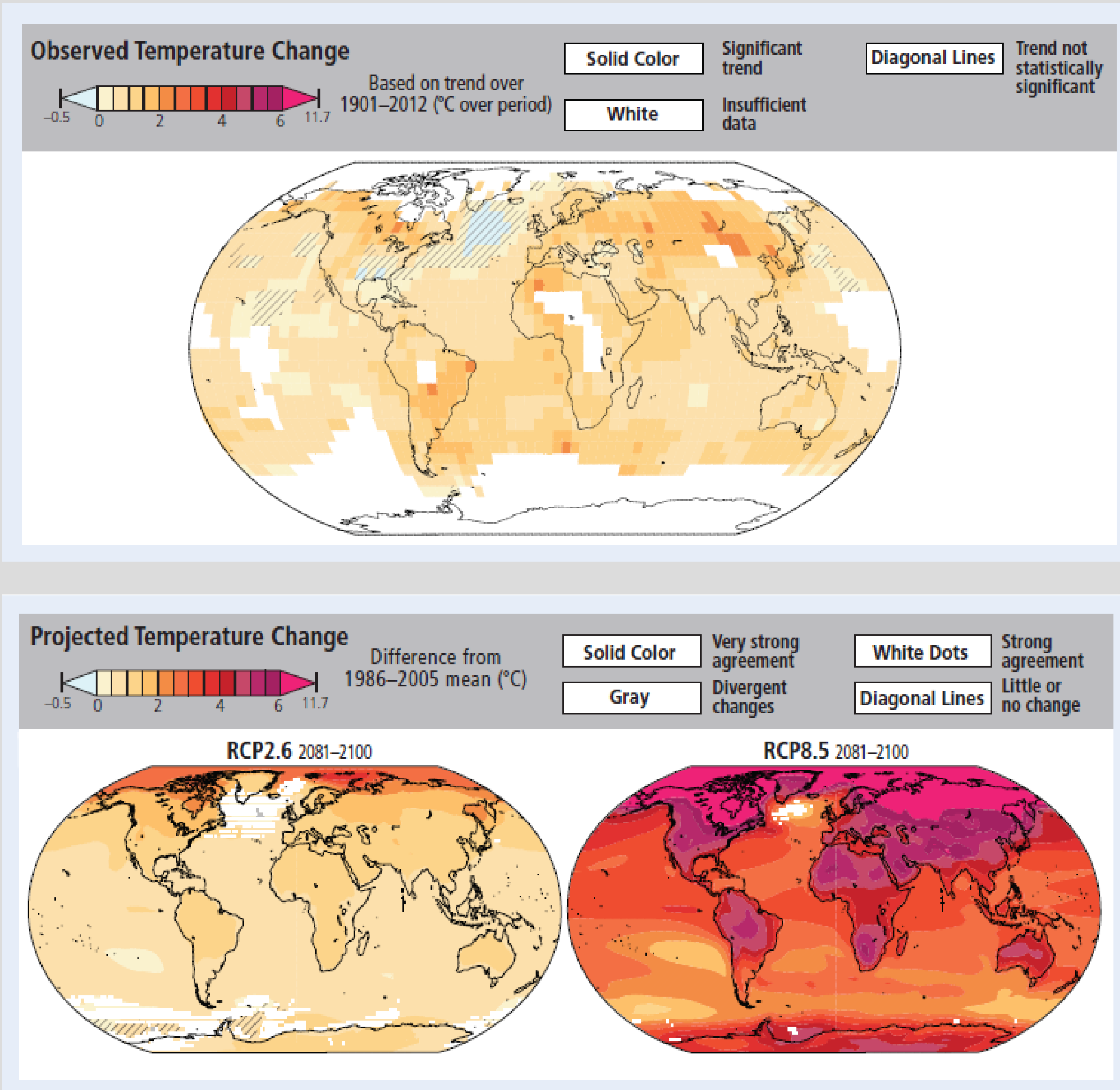
The literature review focuses on first the science and current trends behind climate change as related to sea level rise, storm surge, and coastal flooding. The current and projected trends directly related to our national security, and how the DON as our designated defender of the seas is particularly vulnerable. Once the current risk is discussed, the thesis then transitions into classifying the spectrum of adaptative strategies available to coastal managers.

2.2 Climate Change and Sea Level Rise Science

Climate change is occurring around the world and manifests itself differently according to each region. The shared common trend is the exponential increase in global mean temperature, which has occurred since the industrial revolution. From 1880-2012 the average global temperature increased by more than 0.8° Celsius (IPCC 2014), and in the U.S. average temperature increased 0.7° to 1.1° Celsius from 1895-2012 (Melillo, Richmond, and Yohe, 2014). The significance in this number is that as the Earth moved out of ice ages over the past million years, the global temperature rose a total of 4 to 7 degrees Celsius over about 5,000 years. In the past century alone, the temperature has climbed 0.7 degrees Celsius, roughly ten times faster than the average rate of ice-age-recovery warming (NASA 2016).

The primary driver behind this dramatic increase is not due to the Earth's natural cycle, but instead due to anthropogenic activity, related to increased consumption of fossil fuels, and the associated greenhouse gases produced. The concentration of the main greenhouse gas, carbon dioxide (CO_2), has continued to increase from its preindustrial concentration of approximately 278 parts per million (ppm) to over 391 ppm in September 2012, with the rate of rise now at 1.8 ppm per year (The World Bank 2012). Geological and paleo-climatic evidence makes clear that the present atmospheric CO_2 concentrations are higher than at any time in the last 15 million years (Tripati, Roberts, and Eagle, 2009).

Figure 2: Observed and Projected Temperature Change
(Adapted from IPCC. 2014. *Summary for Policymakers*)



While some climate changes will occur slowly and relatively gradually, others could be rapid and dramatic, leading to unexpected breaking points in natural and social systems (Melillo, Richmond, and Yohe, 2014). To combat climate change a two-part strategy must occur- mitigation in combination with adaptation. More effective mitigation measures can reduce the amount of climate change, and therefore reduce the need for future adaptation. Mitigation is the strategy to reduce the use of fossil fuels and curb greenhouse gas emissions. Adaptation actions are complementary to mitigation actions. They are focused on moderating harmful impacts of current and future climate variability and change and taking advantage of possible opportunities. Such opportunities include the implementation of alternative energy sources, increasing resiliency to built and natural infrastructure, efficiency measures for energy and water usage, and by supporting the health of natural carbon sinks such as forests. Human-induced climate change is projected to continue, and it will accelerate significantly if global emissions of heat-trapping gases continue to increase, a policy of mitigation and adaptation is critical to implement now (Melillo, Richmond, and Yohe, 2014).

Figure 3: Human Activities and the Global Carbon Dioxide Budget
(Melillo, Richmond, and Yohe, 2014)

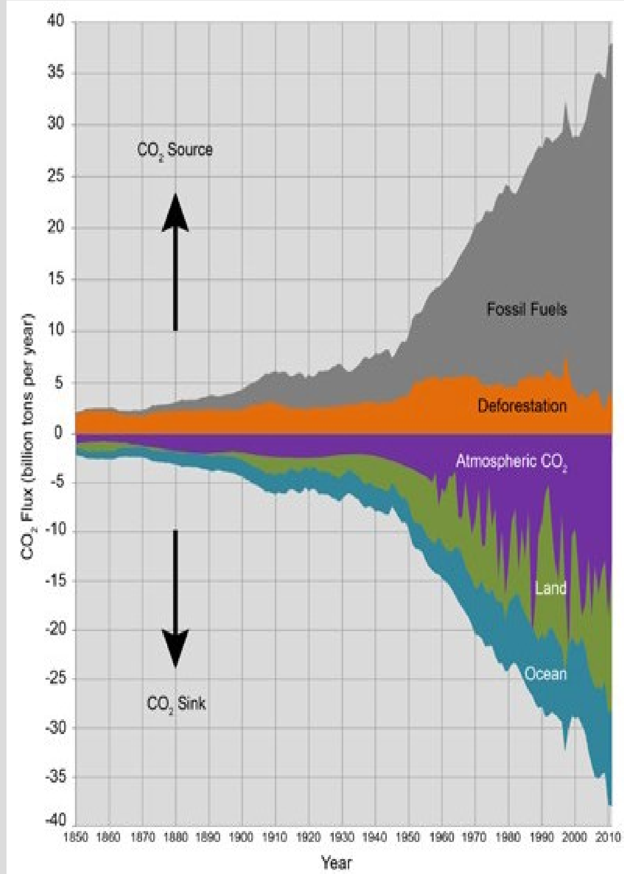


Figure shows human-induced changes in the global carbon dioxide budget roughly since the beginning of the Industrial Revolution. Emissions from fossil fuel burning are the dominant cause of the steep rise shown here from 1850 to 2012.

2.2.1 Observed Climate Change

Although the focus of this thesis is on climate change as related to sea level rise, storm surge, and coastal flooding vulnerability to U.S. military installations, the other meteorological and land effects shall be discussed to demonstrate the linkages of risk both related to infrastructure resiliency and national security. Additionally if the effects of climate change in all forms are understood, then there may be opportunities for adaptation strategies that have co-benefits to other climate-induced threats.

2.2.2 Meteorological and Terrestrial Effects

-*Rising Temperatures*: Climate change is increasing the risks of heat stress, respiratory stress from poor air quality, and the spread of waterborne diseases. Extreme weather events often lead to fatalities and a variety of health impacts on vulnerable populations, including impacts on mental health, such as anxiety and post-traumatic stress disorder (Melillo, Richmond, and Yohe, 2014).

-*Increased Drought:* On a global scale, warming of the lower atmosphere strengthens the hydrologic cycle, mainly because warmer air can hold more water vapor (Coumou and Rahmstorf, 2012; Trenberth 2010). This strengthening causes dry regions to become drier and wet regions to become wetter, something which is also predicted by climate models (Trenberth 2010). Secondary effects of drought include increased wildfires and pest outbreaks.

-*Increased Flooding:* Flooding along rivers, lakes, and in cities following heavy downpours, prolonged rains, and rapid melting of snowpack is exceeding the limits of flood protection infrastructure designed for historical conditions (Melillo, Richmond, and Yohe, 2014). Additionally storm water infrastructure is often undersized, and cannot keep up with the levels of water entering the system.

-*Decreased Agricultural Output:* On the demand side of the food equation, population growth, and the rising conversion of food into fuel for cars and livestock, has raised the consumption rate of agricultural products to its highest rate in history (Gerber et al. 2013). On the supply side, extreme soil erosion, growing water shortages, and the earth's rising temperature are making it more difficult to expand production. 70% of our world's water consumption is related to irrigation for food, and during the last half of the 20th century irrigated lands increased nearly threefold. Since 2000 though, there has only been an increase by 9%. This dramatic loss of momentum in irrigation expansion, coupled with the aquifer depletion that is already reducing irrigated area in some countries, suggests that peak water may now be on our doorstep (Brown 2012).

2.2.3 Ocean and Shoreline Effects

-*Sea Level Rise:* This rise in sea levels is caused by thermal expansion of the oceans and by the addition of water to the oceans as a result of the melting and discharge of ice from mountain glaciers and ice caps and from the much larger Greenland and Antarctic ice sheets (The World Bank 2012). As the sea level rises it inundates low lying coastal regions- waves pound along shorelines above the high tide level causing erosion. Seawater can infiltrate the aquifer and freshwater system, sea water can cause flooding to infrastructure including roads, facilities, underground utilities, and storm water collection systems. Sediment transfer patterns can alter, and it can alter the habitat of the shoreline as animals and plants are forced to shift to new habitat ranges.

-*Storm Surge:* Sea level rise, combined with coastal storms, has increased the risk of erosion, infrastructure damage due to waves, and flooding for coastal communities. Coastal infrastructure, including roads, rail lines, energy infrastructure, airports, port facilities, and military bases, are increasingly at risk from sea level rise and damaging storm surges. Coastal flooding is predominantly caused by storm surges that accompany hurricanes and other storms. Low storm pressure creates strong winds that create and push large seawater domes, often many miles across, toward the shore. The approaching domes can raise the water surface above normal tide levels (storm surge) by more than 25 feet, depending on various storm and shoreline factors. (Melillo, Richmond, and Yohe, 2014). In addition to the increased water level, storm debris can cause major problems along the shore, both damaging property and inflicting harm to human life and safety.

-*Ocean Acidification:* More acidic waters inhibit the formation of shells, skeletons, and coral reefs. Warmer waters harm coral reefs and alter the distribution, abundance, and productivity of many marine species. The rising temperature and changing chemistry of ocean water combine with other stresses, such as overfishing and coastal marine pollution, to alter marine-based food production and harm fishing communities (Melillo, Richmond, and Yohe, 2014). The oceans play a major role as one of the Earth´s large CO2 sinks. As atmospheric CO2 rises, the oceans absorb additional CO2 in an attempt to restore the balance between uptake and release at the oceans' surface (McGregor, Roberts, and Cousins, 2013).

-*Increased Ocean Heat Storage:* While the warming of the surface temperature of the Earth is perhaps one of the most noticeable changes, approximately 93 percent of the additional heat absorbed by the Earth system resulting from an increase in greenhouse gas concentration since 1955 is stored in the ocean (McGregor, Roberts, and Cousins, 2013). Rising ocean temperatures increase vulnerability to algal blooms, migration of fish species to new habitat, and loss of marine animals and corals who are unable to migrate.

-*Loss of Sea Ice and Glaciers:* The IPCC *Climate Change 2014: Impacts, Adaptation, and Vulnerability Report,* indicated a 0.41 ±0.4 mm/year rate of sea-level rise from the ice sheets for the period 1993–2003, while other reports give a 1.3 ±0.4 mm/year for the period 2004–08 (The World Bank 2012). The great concern with the increased melting of sea ice and glaciers is not only habitat loss, but from a security and environmental perspective, ocean sea-lanes are beginning to open up in the Arctic, which could promote increased human activity (DOD 2014, Bhatt et al. 2014).

2.2.4 Sea Level Rise Patterns

Global sea level has risen by about 8 inches since reliable record keeping began in 1880. It is projected to rise another 1 to 4 feet by 2100 (Melillo, Richmond, and Yohe, 2014). Climate change is only one aspect of sea level rise; studies have found that sea level does not rise uniformly around the world. For example, the Pacific and Atlantic Coasts of the United States will experience significantly more sea level rise than the global average (McGregor, Roberts, and Cousins, 2013). The differences can be attributed to the fact that sea level rise is not a linear process; instead the factors below will affect the relative rise:

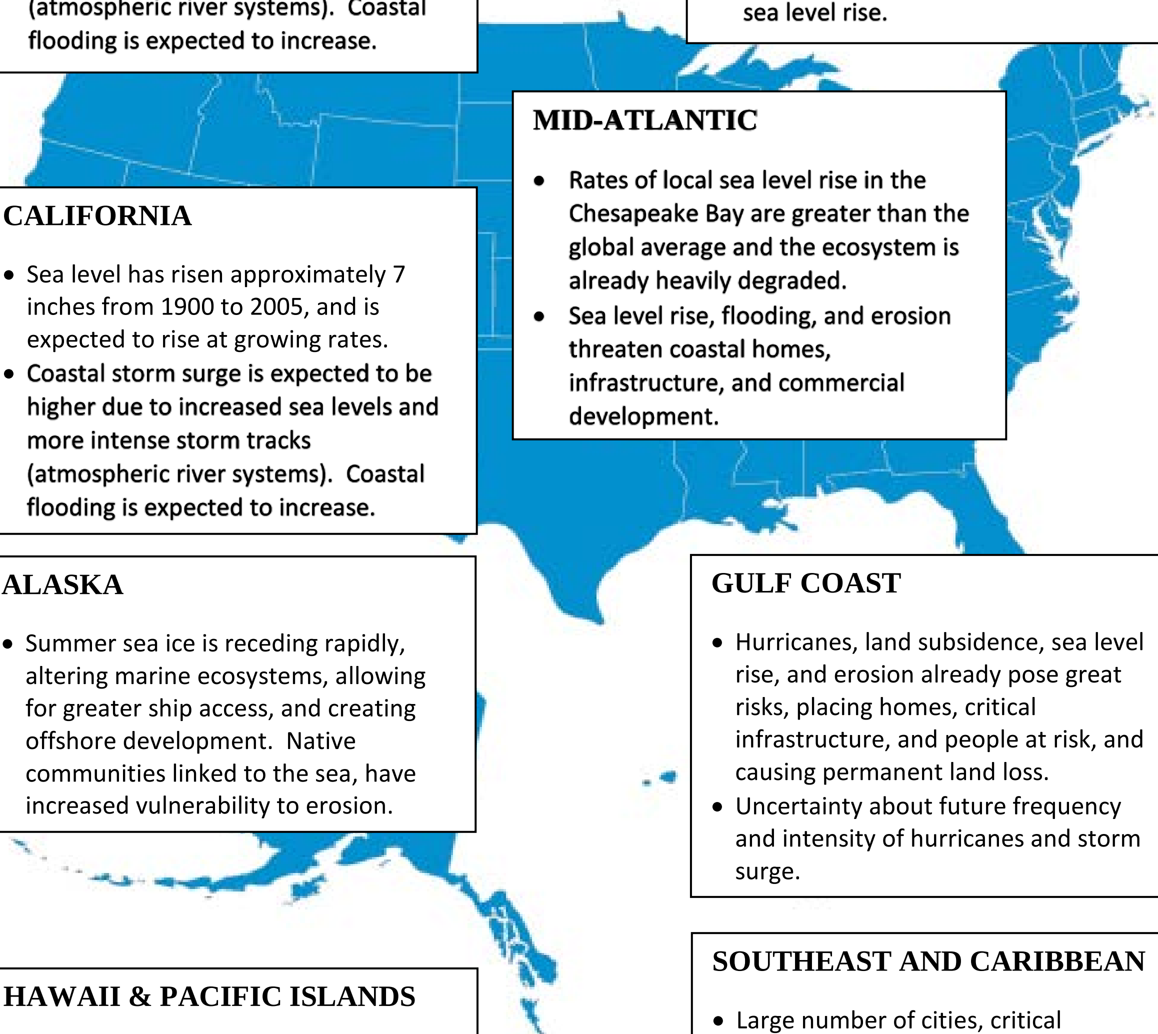
1. Thermal expansion of water, and melting of glaciers.
2. Hydrological impacts of runoff.
3. Groundwater extraction due to lowered surface level water, this extraction lowers relative land elevations.
4. Temporal climate alterations due to El Nino and La Nina.
5. Volcanic and geothermic activity.
6. Vertical land movement associated with glacial isostatic adjustment (Chang, Guan, and Aral, 2015).

In addition to the factors above the relative current height of coastal military installations and composition of their shoreline will directly affect how sea level rise will affect the shoreline and associated infrastructure. Hardened shoreline with armoring and seawalls, dissipate wave energy much differently than natural shorelines.

Due to the complexity of the thousands of miles of shorelines along the United States, patterns are manifesting differently. For planning purposes, military planners in the Mid-Atlantic for example may have very different sea level rise, storm surge, and natural topography to consider when making planning decisions than planners in the southwest.

FIGURE 4: DIFFERENCES IN CLIMATE CHANGE THREATS

(Adapted from Melillo, Richmond, and Yohe, 2014)



PACIFIC NORTHWEST

- Substantial global sea level rise is regionally moderated by the continuing uplift of land, with few exceptions such as in Seattle or central Oregon.
- Coastal storm surge is expected to be higher due to increased sea levels and more intense storm tracks (atmospheric river systems). Coastal flooding is expected to increase.

NORTHEAST

- Highly built-up coastal corridor with concentrated population and supporting infrastructure.
- Wetlands and estuaries are vulnerable to inundation from sea level rise; buildings and infrastructure are most vulnerable to higher storm surge and sea level rise.

MID-ATLANTIC

- Rates of local sea level rise in the Chesapeake Bay are greater than the global average and the ecosystem is already heavily degraded.
- Sea level rise, flooding, and erosion threaten coastal homes, infrastructure, and commercial development.

CALIFORNIA

- Sea level has risen approximately 7 inches from 1900 to 2005, and is expected to rise at growing rates.
- Coastal storm surge is expected to be higher due to increased sea levels and more intense storm tracks (atmospheric river systems). Coastal flooding is expected to increase.

ALASKA

- Summer sea ice is receding rapidly, altering marine ecosystems, allowing for greater ship access, and creating offshore development. Native communities linked to the sea, have increased vulnerability to erosion.

GULF COAST

- Hurricanes, land subsidence, sea level rise, and erosion already pose great risks, placing homes, critical infrastructure, and people at risk, and causing permanent land loss.
- Uncertainty about future frequency and intensity of hurricanes and storm surge.

HAWAII & PACIFIC ISLANDS

- Sea level rise will continue at accelerating rates, exacerbating coastal erosion, damaging infrastructure and agriculture. Large reduction in critical habitat, and shallow coral reef systems.

SOUTHEAST AND CARIBBEAN

- Large number of cities, critical infrastructure, and water supplies are at low elevations and exposed to sea level rise.
- Ecosystems are vulnerable to loss from relative sea level rise, especially tidal marshes and swamps.

2.2.5 Sea Level Rise Scenarios

Sea level rise because of the relative high population, infrastructure development, and concentration of naval installations along the coastline, presents one of the largest threats related to climate change. Projecting sea-level rise as a consequence of climate change is one of the most difficult, complex, and controversial scientific problems. Process-based approaches dominate—i.e the use of numeric models that represent the physical processes at play—and are usually used to project future climate changes such as air, temperature, and precipitation (The World Bank 2012). According to NOAA they have very high confidence (>9 in 10 chance) that global mean sea level will rise at least 0.21 meters (8 inches) and no more than 2.0 meters (6.6 feet) by 2100 (Parris et al, 2012). Due to the complexity of predicting overall ocean warming, and glacier and ice sheet melting primarily from West Antarctica and Greenland, NOAA has projected 4 scenarios that takes into place the best and worst-case scenario. Each scenario is based off of the following assumptions as described in the NOAA report *Global Sea Level Rise Scenarios for the United States National Climate Assessment* (Parris *et al* 2012).

Table 1: Global Sea Level Rise Scenarios
(Adapted from Parris et al. 2012)

Scenario	**Sea Level Rise by 2100**	
Highest	6.6 FT	2.0 M
Intermediate-High	3.9 FT	1.18 M
Intermediate-Low	1.6 FT	0.9 M
Lowest	0.7 FT	0.21 M

Highest Scenario: Derived from a combination of estimated ocean warming from the IPCC AR4[5] global SLR projections and a calculation of the maximum possible glacier and ice sheet loss by the end of the century.

Intermediate-High Scenario: Based on an average of the high end of semi-empirical, global SLR projections. Semi-empirical projections utilize statistical relationships between observed global sea level change, including recent ice sheet loss, and air temperature. The key to this projection is the assumption of continued ice sheet melting, along with ocean warming.

Intermediate-Low Scenario: Based on the upper end of IPCC Fourth Assessment Report (AR4) global SLR projections resulting from climate models using the B1 emissions scenario. The key to this projection is that is considers overall ocean warming temperatures as the primary factor.

Lowest Scenario: Based on a linear extrapolation of the historical SLR rate derived from tide gauge records beginning in 1900 (1.7 mm/yr). Global sea level has risen 0.2 meters (8 inches) over this period of record, and we anticipate at least 8 inches by 2100.

The application of each scenario estimate must be determined on a case by case scenario. For example, coastlines that have critical infrastructure with long life cycles such as a major utility plant or transportation system should consider using the highest projection of sea level rise due to the risk associated with damage to the critical infrastructure. Additionally locational patterns such as subsidence taking place along the California coastline south of Cape Mendocino or continental uplift north of Cape Mendocino along the Northern California, Oregon, and Washington coast should be considered when planning for sea level rise projections.

The DOD recognizing the uncertainties of predicting sea level rise at its 1813 coastal military sites worldwide, developed and published as of August 2016, the Sea Level Rise (SLR) and Extreme

[5] AR4 is the IPCC's fourth report in the series and published in 2007. It documented the current science and model based predictions of future climate change effects.

Water Level (EWL) Scenario database website. The tool provides localized information on future SLR and EWL for three time horizons (2035, 2065, and 2100) to assist with climate change adaptation planning for DOD coastal and tidally influenced sites worldwide. These scenarios provide a decision-maker with temporal and physically based information to assess future vulnerabilities. Although these scenarios are intended to be used in a "screening" context and not detailed engineering design, their development collectively represents several advancements in scenario development for coastal locations that can serve as a starting point for other applications (DOD 2016b).

Military planners now have access to global predictions of sea level rise from low to high scenarios, but also can further refine those predictions by using the Sea Level Rise (SLR) and Extreme Water Level (EWL) Scenario database. To reiterate projections are merely that, the best educated guess with the science and observations at hand. Military planners must assess their local site patterns for observed shoreline phenomena, development patterns, and infrastructure risks. Localized risk assessments shall be discussed further in section 4.1 Vulnerability Analysis.

2.3 Security Related to Climate Change

Climate Change, massive urban growth, and great social and economic disparity in the 21st century has caused the United States Government and Military to reassess their security strategy. In order to remain secure at home and abroad, the United States must place high priority on mitigation and adaptive strategies against climate change at home. The impacts of climate change may increase the frequency, scale, and complexity of future missions, including Defense Support to Civil Authorities (DSCA), while at the same time undermining the capacity of our domestic installations to support training activities (DOD 2014a). As our global economy grows, more and more people around the world are moving to cities for the hope of employment and a better way of life. Not only is our world becoming more urban, but also the level of density and scale is increasing. Developing countries are at much more risk of not being able to maintain a critical balance of resources such as food, water, and electricity, and with the threat of climate change, that fragile balance is threatened. Climate change not only deteriorates our environmental resilience, but also threatens to exacerbate social inequalities against the poor and vulnerable.

The world's population continues to increase exponentially every year, and with that growth comes continued strain on our resources, urban infrastructure, and government cohesion. We are entering a new era of rising food prices, spreading hunger, and lack of freshwater. On the demand side of the food and water equation, is the combination of population growth and rising desire to convert food into fuel for cars. On the supply side, extreme soil erosion, growing water shortages, and the earth's rising temperature are making it more difficult to expand production of food (Brown 2011). The second half of the 20th century experienced bountiful food and grain production, enough that surpluses could be stored in the event of a shortage in some vulnerable part of the world. During the first portion of the 21st century, that surplus has dramatically changed to a deficiency, in which farmers are barely making enough for each year. According to the United Nations, Over 1 Billion people are going hungry, often going days at a time without food. Our most vulnerable population around the world, children are being malnourished, and mentally and physically not developing to their full potential. As climate change affects the availability of food and water, human migration, and competition for natural resources, the DOD's unique capability to provide logistical, material, and security assistance on a massive scale or in rapid fashion may be called upon with increasing frequency (DOD 2014a).

The lack of food and water increases the price of food, and although for Americans who only spend on average 9 percent of their income on food, there are consumers in developing countries who spend 50-70 percent of their income on food (Brown 2012). This is not a sustainable condition, any additional variable may cause mass amount of people to act out in desperation and/or anger towards their government. Fundamentally, humans need their basic needs of shelter, food, and water to feel secure in their environment, when those basic needs are taken from them due to primary or secondary effects of climate change, they will either move or act out against those who they see as their oppressor. It takes whatever underlying social weaknesses exist and magnifies them. For countries where social safety nets or alternative sources of income are lacking, underemployed and disenfranchised youth are the obvious targets of radicalization (Barbut 2014).

Simply put, a threat to food, water, and natural resource security is a threat to international security. However, the growing tyranny of a changing climate and oppression of food insecurity and poverty are creating social instability all over the world. This new trend has emerged repeatedly, from Darfur in North Africa, the Middle East and parts of South Asia. As the choices for survival diminish, the poor are forced to take a stand to fight for their survival or flee. It is estimated that as many as 60 million people could move from North Africa to Europe in a 15-year period (Barbut 2014). Mass migration as demonstrated currently by Syrian refugees fleeing to Europe, causes great social turmoil for the refugees, but also leaves the receiving country with economic strain, weakens host nation resources, and often creates tension or hostility, as multiple cultures are forcefully mixed at an exponential rate.

2.3.1 Security and Infrastructure in the Continental United States

The DOD maintains more than 1,200 military installations in the United States alone—sites where the military tests weaponry, conducts training exercises, builds and launches ships, compiles intelligence, develops new technology, and houses critical military commands (Hall et al. 2016). Military installations are known to be well fortified, and have advance physical and human security procedures to counter any potential threat. The concept of threat is changing though; to our natural environment and the devastating affects sea level rise, coastal flooding, and violent storm surge can do the infrastructure and readiness of military personnel. A roughly three-foot increase in sea level would threaten 128 coastal DOD installations in the United States (43 percent of which are naval installations, valued at roughly $100 billion) and the livelihoods of the people—both military personnel and civilians—who depend on them (NAS 2011).

With a steady decrease in the military budget since 2010, the current proposed military budget of $582.7 billion is a 2.4 billion increase from the FY 2016 budget. The FY 2017 budget reflects recent strategic threats and changes that have taken place in Asia, the Middle East and Europe (DOD 2016c). The decrease in budget can be attributed to the withdrawal of major military efforts in Iraq and Afghanistan. The concern though, is during the prolonged period the United States military was at war, funds were prioritized towards operational efforts, not maintenance efforts of installation facilities and utility infrastructure. Military built infrastructure with deferred maintenance, and rising risk of climate change and sea level rise, will become increasingly more vulnerable. Infrastructure and facilities with deferred maintenance is a concern, in that it implies that the quality and reliability of service provided by infrastructure on which maintenance has been deferred is lower than it should be (Dowall and Whittington, 2003).

Although the DOD has been formally warning of climate change and related impacts all the way back to the 2008 National Intelligence Assessment issued during the Bush Administration, there is debate within Congress on the risk, and in return designated funds have not been set aside for mitigation and adaptation. In accordance with the direction in Executive Order 13653, the DOD issued *DOD DIRECTIVE 4715.21 Climate Change Adaptation and Resilience* establishing policy and assigning responsibilities to specific departments. Many of the Departments are already operating at lower budgets, and to mitigate and adapt proactively it will cost the DOD. On June 16, 2016, Congress passed amendment 216/205, which prohibits funds to implement *DOD DIRECTIVE 4715.21 on Climate Change Adaption and Resilience*, requiring the Pentagon to prioritize funding related to national security threats operationally (United States Congress 2016). The concern with this amendment is that it creates mixed signals to the DOD, although former President Obama had placed priority on the risk of climate change to our national security, Congress restricted any funding to the executive order.

2.4 Department of Defense Policy

The Department's ability to deploy quickly and effectively depends on a well-functioning infrastructure of military installations, testing, and training grounds that are secure from threats. Climate change introduces an added risk factor, particularly for those installations and sites along the coast worldwide

(Samaras 2015). The Department of Defense through the *2014 Climate Change Adaptation Roadmap* has established three broad adaptation goals, which are made into achievable actions through four areas of effort.

Goal 1: Identify and assess the effects of climate change on the Department.

Goal 2: Integrate climate change considerations across the Department and manage associated risks.

Goal 3: Collaborate with internal and external stakeholders on climate change challenges.

Areas of effort include: *Plans and Operations, Training and Testing, Built and Natural Infrastructure*, and *Acquisition and Supply Chain* (DOD 2014a). For the purpose of this thesis, *Built and Natural Infrastructure is* the lens of focus. *Built and Natural Infrastructure* are both necessary for successful mission preparedness and readiness. While built infrastructure serves as the staging platform for the Department's national defense and humanitarian missions, natural infrastructure also supports military combat readiness by providing realistic combat conditions and vital resources to personnel (DOD 2014a).

The Department of Defense recognizes that climate change mitigation and adaptation must be viewed in a long-term strategic sense, and has primarily focused its efforts as of today in issuing policy and assigning responsibility for action, they have also been in the information-gathering phase. Collecting data, reviewing trends, and using the best available science to create metrics. As the former Secretary of Defense Chuck Hagel stated "Drawing on these assessments, we are integrating climate change considerations into our plans, operations, and training across the Department so that we can manage associated risks. We are considering the impacts of climate change in our war games and defense planning scenarios, and are working with our Combatant Commands to address impacts in their areas of responsibility" (DOD 2014a).

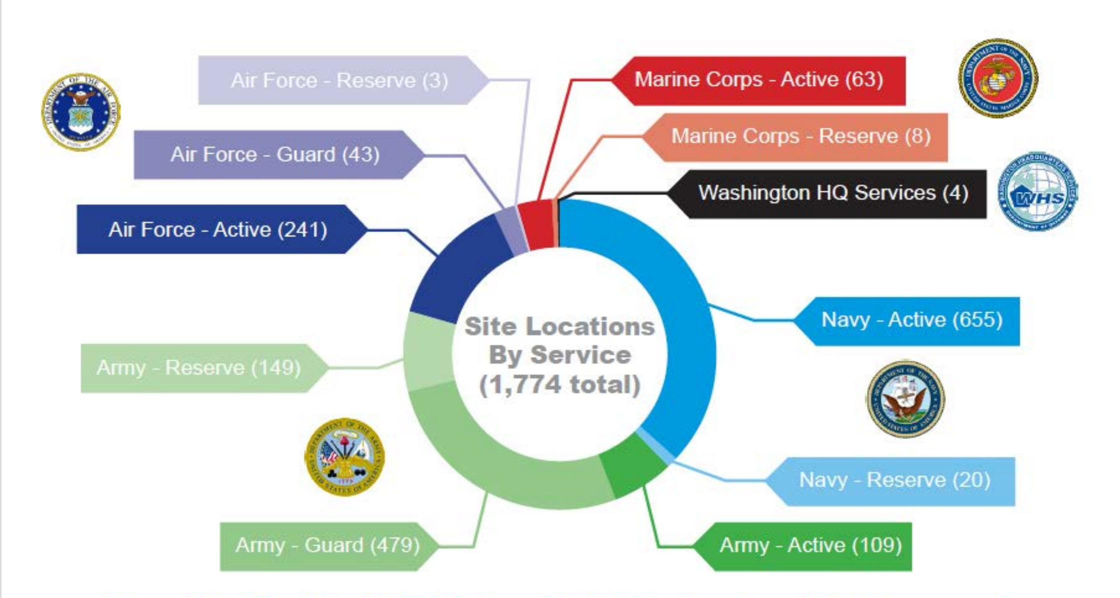
2.4.1 Department of Defense Installation Vulnerability

Given that around 10 percent of U.S. military installations and training grounds are located along low-lying and exposed coastlines, the long-term effects in terms of flooding will be significant (SERDP 2013). As noted by The Strategic Environmental Research and Development Program (SERDP), the DOD's environmental research program, potential risks to installations include:

- Loss or damage to mission essential infrastructure including coastal development; energy and water infrastructure;
- Loss or degradation of mission capabilities;
- Loss of training and testing lands, including beaches and barrier islands;
- Loss of transportation means, facilities, and/or corridors;
- Loss of habitat and associated natural resources;
- Increased risk of storm damage and coastal erosion; and,
- Increased potential for loss of life.

According to SERDP there are 1774 military installations or sites around the world that are considered to be in coastal environments or are affected by tidal fluctuations. A site can be defined as smaller areas with permanent infrastructure that are administratively assigned to a parent, or primary, installation, regardless of whether the site is located in proximity to that parent installation (SERDP 2013). Of those 1774 sites, the Navy is responsible for 675 or 38%, if the Marine Corp which is a part of the Department of Navy is considered also, then the DON is responsible for 42% of the entire DOD installations along the coastline. When all considered, The Department of Navy with the majority of the active installations along the coastline, its Atlantic and Pacific fleet of ship along the coast, and several of its Naval Air Stations concentrated along the coast, has a huge vulnerability to sea level rise and associated flooding.

Figure 5: U.S. Military Installations or Sites Within a Coastal Environment
(Adapted from SERDP 2013)



2.4.2 Department of Defense Weaknesses or Missing Policy

The Assistant Secretary of Defense for Energy, Installations, and Environment (EI&E)[6] is specifically charged in the *2016 DOD Directive 4715.21- Climate Change Adaptation and Resilience*, to be the responsible agent for the DOD's adaptation strategy and implementation for infrastructure and facilities. As related to the resiliency of our built infrastructure, with any large institution though, it is challenging and takes time to produce any firm policy guidance on actual building or planning standards. The Department of Defense follows the Unified Facilities Criteria for design codes of all facilities, at this time the code is undergoing review, but has not been updated to incorporate the risk of climate change or specifically sea level rise. Additionally at this time there are no funding streams specifically set aside within the Department of Defense for countering climate change.

[6] The Assistant Secretary of Defense for Energy, Installations, and Environment ASD (EI&E) provides budgetary, policy, and management oversight of the Department of Defense's (DoD): acquisition and use of operational and installation energy to support warfighting and base operations, which encompasses energy security, increased energy efficiency, and promotion of renewable energy sources (DOD 2016d)

2.5 Department of Navy Policy

The DON was one of the first services to acknowledge and issue policy on climate change, and they have viewed climate change through an operational fleet and shore based infrastructure lens. Specific strategy was issued in the *2010 Navy Climate Change Road Map*, which broke down policy into 3 phases to occur between 2010-2014. Phase 1 (FY10) required inclusion of climate change on coursework in the Naval War College, and definition of operational and climatic prediction capability. Phase 2 (FY11-12) required climate change to be incorporated into strategic documents, formalization of relationships to assess, predict, and adapt to climate change. Phase 3 (FY13-14) inclusion of initiatives in the POM-14 budget and further ability to assess, predict, and adapt to climate change. The real action items of the roadmap were defined in "action items" in which individual lead organizations within the Navy were assigned responsibility or support responsibility. NAVFAC as the Navy's designated command which builds and maintains facilities, provides utilities, and overseas environmental compliance on naval installations, was charged with the following actions items:

- Serve as a member of Task Force Climate Change.
- Action Item 1.3U Propose additional studies and research regarding the national security implications of climate change on Naval missions, force structure, and infrastructure.
- Action Item 3.1 Initiate a Navy Climate Change Adaptation Capabilities Based Assessment (CBA).
    - This action item is also to specifically address:

      Additional Current and required capability of infrastructure to adapt to climate change, with particular emphasis on sea level rise and impacts on installations' natural and cultural resources.
- Action Item 3.2 Identify Climate Change Science and Technology (S&T) Needs.

- Action Item 3.3 Beginning with POM-14 and biennially each POM year thereafter, assess guidance in the Navy Strategic Plan (NSP) (Action Item 1.5), if any, relating to climate change assessment, prediction, and adaptation, and address these requirements in Sponsor Program Proposals (SPPs).
- Action Item 5.1 Begin monitoring, accounting, tracking, and reporting Navy GHG emissions in accordance with EO 13514.30 (DON 2010).

NAVFAC is a lead member of the Navy Climate Change Task Force, and internally has periodic meetings throughout the year with NAVFAC Facilities Engineering Command Commanders, Public Works Officers, Energy Managers, and any interested NAVFAC personnel to distribute current policy and initiatives. At this time, there is no defined risk analysis, design guidance, or fiscal policy on climate change from an adaptation perspective.

NAVFAC has made significant strides in their energy policies and procedures, which are directly related to climate change mitigation, although not specifically called out in policy as a "climate change mitigation" effort. The goal of the Navy Shore Energy Program is to reduce shore energy intensity by 30% (energy consumption per square foot) by 2015 (compared to 2003 baseline) and by 50% in 2020, while providing reliable energy to 100% of Navy Tier I/II Critical Assets.[7] This goal positions the Navy to achieve legal and regulatory compliance related to shore energy, water management, and reduced carbon footprint, in addition to achieving the SECNAV's energy targets. These targets require the reduction of shore energy consumption by 50% and require production of at least 50% of shore based energy requirements from alternative sources (CNIC 2016).

[7] Tier 1 An asset the loss, incapacitation, or disruption of which could result in mission (or function) failure.
Tier 2 An asset the loss, incapacitation, or disruption of which could result in severe mission (or function) degradation.

2.5.1 Department of Navy Installation Vulnerability

Due to the nature of the Navy's mission, the concentration of naval assets (ships and aircraft) and support shore infrastructure are concentrated along the coastline. The Navy's Atlantic Fleet is concentrated at Naval Station Norfolk, Virginia established in 1917, and Naval Station Mayport, Florida established in 1942. The Pacific Fleet is concentrated with Fleet headquarters at Pearl Harbor Naval Station, Hawaii established 1923, and large secondary installation at Naval Air Station North Island established 1917 and Naval Base San Diego established 1920. This is only a snapshot of the installations the Navy operates, but it does demonstrate that some of the primary installations are coming upon their 100th year anniversary, in which planning and initial infrastructure decisions were made without the concern of sea level rise or strong storm surge.

Exposure to damage from future sea level rise for naval installations will vary from locality to locality. Some specific impacts that can be anticipated include effects on piers, utilities, and freshwater. Piers will be affected by the sea level relative to the height of the pier as the force exerted by the ship and waves on the pier may grow to be outside the original structural design criteria (National Academies Press 2011). Other critical infrastructure includes electrical substations and vaults, water distribution, storm water systems, overhead utilities, and support facilities that include, but are not limited to administrative offices, supply warehouses, runways, aviation hangars, weapon storage facilities, and berthing.

Table 2: Summary of Port Infrastructure Vulnerability
(Adapted from Kong 2013)

Climate Change Variable	Direct Impact on Infrastructure	Indirect Impact
Infrastructure: Berthing (Pier, Dock)		
Increased severity of weather events (including rainfall, wind, cyclones, and sea storms)	Infrastructure damage and deterioration resulting from heavy storm activity	Increased maintenance and replacement costs
Sea level rise	Inundation of infrastructure	Increased risk of liability from port damage
Increased ocean swell	Shifting tidal and splash zone level	
Ocean acidification		

Table 2: Summary of Port Infrastructure Vulnerability (Continued)
(Adapted from Kong 2013)

Climate Change Variable	Direct Impact on Infrastructure	Indirect Impact
Infrastructure: Protecting Barrier (Breakwater, Bulkheads, Revetment)		
Increased severity of weather events (including rainfall, wind, cyclones, and sea storms)	Increased wave overtopping of protection barriers	Exposure of harbor to ocean swells
Sea level rise	Barrier material displacement or fracture	Increased maintenance and replacement costs
Increased ocean swell	Erosion of barriers	Shipping delays
		Damage to cargo and goods
		Increased risk of liability resulting from port damage
Natural Infrastructure: Port Superstructure (Admin, Warehouse, Support Facilities)		
Increased variation wet/dry spells	Failure of foundation	Damage to cargo and goods
Increased temperature and heatwave	Degradation of superstructure materials	Increased cost of operations
Increase in extreme rainfall	Increased storm and flood damage	Increased maintenance and replacement costs
Increased intensity of extreme wind	Failure of roof and cladding	Increased risk of liability resulting from port damage
Sea Level Rise		
Infrastructure: Natural (Shoreline, Channel, Harbor Basin)		
Wave Action	Change in water depth	Bank failure
Precipitation (Increase/Decrease)	Change in water flow	Increased loads on structures
Changes in seasonal precipitation	Increased/decreased sedimentation	Changes in ship maneuverability
Sea level rise	Change in timing of seasonal high water and seasonal low water	Reduced regularity of port traffic
Storms		
Storm surge		
Infrastructure: Road		
Increased temperatures and solar radiation	Embrittlement and cracking bitumen	Increased maintenance costs to increase resilience
Increased temperatures and heatwaves	Loss of water seal causing potholing	Temporary blocked road access. Rerouting to avoid affected roads
Increased rainfall	Low lying roads may be submerged	Interruption to commercial activities that depend on road transport
Increased variation wet/dry spells	Damage to road foundations as a result of prolonged drought and low rainfall	
Sea level rise		
Flooding		

2.5.2 Department of Navy Weaknesses or Missing Policy

Although there is significant policy placing priority on combatting climate change and sea level rise, and numerous sources of data demonstrating the threat, there is no one guidance document or decision framework in order to assess risk, and make educated adaptive decisions. NAVFAC's *2016 Strategic Design Document*, which sets the priorities of the command has no mention of climate change, although energy efficiency and security are referenced (NAVFAC 2016). NAVFAC as the custodian of naval shore based infrastructure has an invested interest in assuring its military leaders and facilities engineers are first assessing and planning for climate change risk, and second should be incorporating adaptation efforts for sea level rise, storm surge, and flooding into financial budgets, planning initiatives, new design efforts, and maintenance procedures for existing infrastructure.

2.6 Risk Identification

Risk is defined in terms of the likelihood that an event will occur at a given location within a given time period and will inflict casualties and damage. This risk must be effectively communicated to the people who are likely to be affected so they can receive, heed, and comprehend the risk (Lindell et al. 2006). Risk must be viewed through varying scales, and time sensitivities. Sea level rise is a risk that although can inflict major damage, can be assessed, and properly addressed in a time frame that is measured in years, both the short-term 1-5 years out, to mid and long-term (5 or more years) depending on site specific conditions. In contrast though, depending on existing conditions, storm surge and coastal flooding may be a risk that although infrequent, could occur in any time frame.

Risk is determined by evaluating three factors that contribute to risk. *Vulnerability* is the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climate change, including climate variability (The World Bank 2013). This includes the resources both material and financial, available to respond or address climate change or climate related disasters. *Exposure* is concerned with the physical infrastructure, assets, and people who are within the projected inundation or flood zone. The third element that generates risk is the *Natural Hazard* that presents the threat, in the application of this thesis- sea level rise, storm surge and coastal flooding is the threat, and the level of threat is based off of localized projections and climate history.

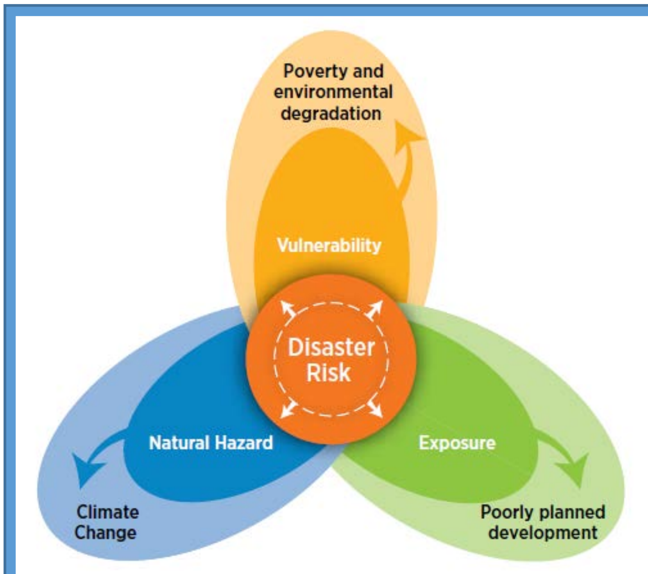


Figure 6: The Role Natural Hazards, Exposure, and Vulnerability Have in Risk
(Adapted from The World Bank, 2013)

The purpose of a risk assessment is to define the risk, answer questions about characteristics of potential hazards (such as frequency and severity), and identify vulnerabilities of communities and potential exposure to given hazards. Risk evaluation helps in prioritizing measures for risk management, giving due consideration to the probability and impact of potential events, cost-effectiveness of preventative measures, and resource availability (Dickson et al. 2012). A thorough risk evaluation allows planners and decisions makers the opportunity to balance, accept, or diminish risk in a systematic approach, ultimately to increase resiliency for the physical factors of the environment and infrastructure within an installation, and the operational factors that include sea, air, special operations and personnel assets.

2.6.1 Risk Identification Naval Policy

The United States Navy has detailed plans at each installation for emergency management, and how each supporting command and department would be responsible during a natural disaster. Designated emergency managers, who are either civilian certified emergency managers for larger installations, or trained military personal for smaller installations, serve as the Installation Command Officers (ICO) lead on assessing, planning, training, and ultimately responding to a disaster. NAVFAC as the lead organization for management of infrastructure and facilities is a part of the emergency management team, and advises the ICO and installation emergency manager on risks associated with facilities. Although NAVFAC has been intimately involved with emergency management planning associated with natural disasters that have historically impacted bases, including storm surge and flooding scenarios, there is still a lapse in planning for risk associated with sea level rise. Sea level rise occurs at a slow rate compared to a storm surge or a coastal flood, and to this point as demonstrated in the DON's Sea Level Rise policy discussed above, has not been a primary focus of planning for the NAVFAC.

A proper risk assessment for each Naval installation must be conducted to first identify the risks and likelihood of damage associated with sea level rise, storm surge, and coastal flooding to installation infrastructure, equipment, operations, and people, and second what time frame are those risks anticipated to come to fruition. Once a proper risk assessment is conducted related to infrastructure, NAVFAC will be able to advise the ICO and installation emergency manager on what needs to be addressed via emergency management protocols or response procedures in the event of a disaster, versus what needs to be addressed through an infrastructure mitigation or adaptation strategy.

2.7 Climate Change Mitigation and Adaptation

Mitigation and adaptation are closely linked, but have different strategies. Mitigation refers to actions that reduce the human contribution to the planetary greenhouse effect. Mitigation actions include lowering emissions of greenhouse gases like carbon dioxide and methane, and particles like black carbon (soot) that have a warming effect (Melillo, Richmond, and Yohe, 2014). In an essence mitigation effort are preventative efforts, which encompasses reduction of our use of fossil fuels and lowering the amounts of greenhouse gasses that are emitted into the environment.

Mitigation efforts include reducing energy consumption by system components, including efficiency measures applied to: infrastructure, vehicles, manufacturing processes, or electrical devices and appliances. Mitigation encourages use of alternative forms of energy such as wind, solar, geothermal, hydroelectric, or nuclear, versus dependence on fossil fuel forms of energy. Lastly by lowering methane emissions from energy and waste, transitioning to climate-friendly alternatives from hydrofluorocarbons (HFCs), cutting methane and nitrous oxide emissions from agriculture, and improving combustion efficiency and means of particulate capture, mitigation can be achieved (Melillo, Richmond, and Yohe, 2014). In order to effectively mitigate a baseline standard needs to be established for current greenhouse emissions at a federal, state, city or agency level, and then those entities must set goals of reduction that can be tracked and enforced on a regular schedule.

Adaptation in contrast is the adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects (Melillo, Richmond, and Yohe, 2014). Adaptation is the primary focus of this thesis, and is explored through the lenses of *Protect, Accommodate, or Retreat*. *Protect* includes building hardened infrastructure to withstand rising sea levels, or encourages the use of natural shorelines to withstand rising sea levels, storm surge, or flooding. *Accommodate* allows floodwaters or storm surge to approach the site or facility, but encourages the site or infrastructure to build in increased resiliency through construction or planning mechanisms to withstand the damages of water infiltration. Lastly *retreat* is the strategy to allow the shoreline to shift as sea level rises, and through relocation of development risk is decreased.

Successful strategies to combat climate change and sea level rise focus on a multi-pronged effort of mitigation and adaptation, while first assessing the unique risks of each installation. Risk is a combination of the magnitude of the potential consequence(s) of climate change impact(s) and the likelihood that the consequence(s) will occur (Melillo, Richmond, and Yohe, 2014). Risk should be viewed through multiple lenses, including risk to human health, infrastructure damage, and environmental degradation, but in the context of the military risk is also associated with operational risk, and not being able to perform an assigned task related to national security. The strategies employed to counter risk are ultimately done to increase resiliency along our shorelines and infrastructure, which promotes both human and operational resiliency. Resiliency in the context of human social terms is “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker 2004).

2.7.1 Department of Defense Mitigation Efforts through Energy Policy

The DOD and specifically the Navy have demonstrated strong mitigation practices through their energy policies. The DOD views energy efficiency and renewable energy as a benefit to operational mission effectiveness, the environment, climate mitigation, and the bottom line, as outlined in the following excerpt from a 2010 Memorandum of Understanding between DoD and the Department of Energy (DOE):

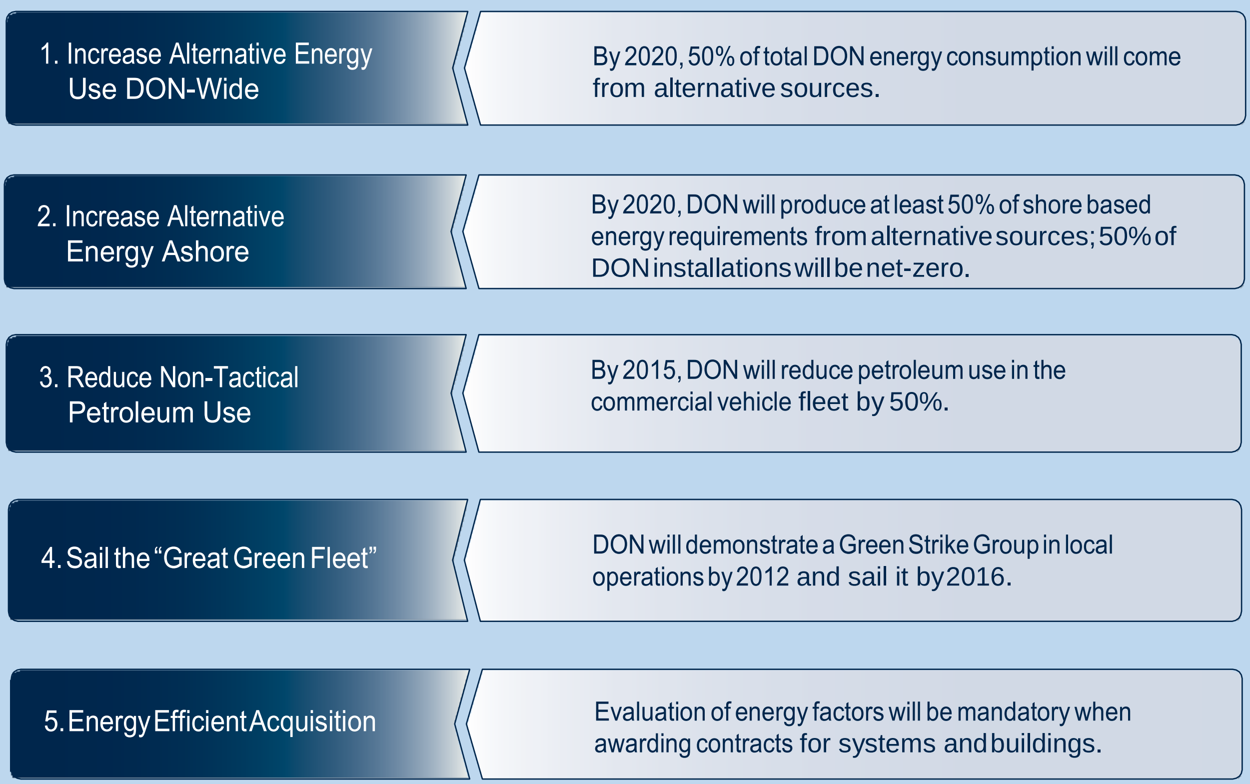
> Energy efficiency can serve as a force multiplier, increasing the range and endurance of forces in the field while reducing the number of combat forces diverted to protect energy supply lines, as well as reducing long-term energy costs. DoD is also increasing its use of renewable energy supplies and reducing energy demand to improve energy security and operational effectiveness, reduce greenhouse gas (GHG) emissions in support of U.S. climate change initiatives, and protect the DoD from energy price fluctuations. Solving military challenges through innovation has the potential to yield spin-off technologies that benefit the civilian community as well.

The DOD provided original policy for installation energy goals in December 2009 through *DoDI 4170.11, "Installation Energy Management"*, which was updated March 2016. Each service is required to interpret the guidance, and establish their own goals and objectives. The Navy has been seen as one of the leaders within the DOD, and had already established aggressive energy goals in October 2009, two months prior to the initial DOD announcement.

2.7.2 Department of Navy Mitigation Efforts through Energy Policy

Energy bills are the single largest cost for Navy installations, reflecting about 28% of Navy's shore budget. The Navy must reduce energy costs to free up scarce budget dollars to support training and fleet operations, and in doing so co-benefits of reduced dependency on foreign fossil fuels occurs, while also reducing the Navy's carbon footprint (CNIC 2016). Secretary of the Navy Ray Maybus in October 2009 issued five critical strategies for the Navy's energy policy, four are critical to installation energy management (goal 1, 2, 3, and 5).

Figure 7: Department of Navy Energy Goals
(Adapted from DON 2012)



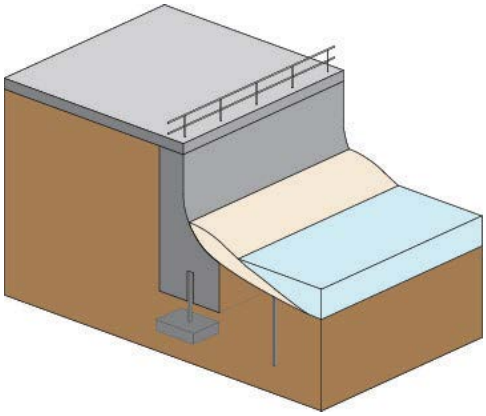
2.8 Adaptation Strategies

Adaptation efforts in the DOD and DON have been lacking compared to the mitigation efforts. Coastal managers and planners are faced with challenging decisions on how to counter climate change and associated sea level rise. Often they feel unprepared, and pressured to make quick decisions without a clear understanding of all options (Langridge et al. 2014). There are numerous options available, and all can be classified under one of the following adaptation categories: *Protect, Accommodate, or Retreat*. Each category is explored below, and although each strategy must be viewed relevant to localized threat, localized mission, and existing infrastructure both physical and natural, the analysis below is a consolidated list of viable options. Ultimately the goal of adaptation for coastal managers is to: (1) Avoid development in areas vulnerable to inundation; (2) Ensure that critical natural systems continue to function; and (3) Protect human lives, essential properties, and economic activities against the ravages of the sea (Jansen 1990). In the context of a military installation an additional goal is paramount, (4) Sustain and support military operations.

2.9 Protect

Defense of vulnerable areas, especially population centers, economic activities, and natural resources (Dronkers et al. 1900). In the spectrum of adaptation strategies protect is the most assertive action by humans against the threats of sea level rise. The attempt is to protect structures, infrastructure, assets, and human life from the intrusion of water, tidal flooding, shore erosion, or damaging effects of strong waves and storm surge. Protection is viewed through two lenses, either "hard" or "soft" measures. Hard measures use physical structure, engineering, and create defined lines between the sea and land. Soft measures employ nature-based strategies, and the line between where the water and land begin is blurred. One strategy is not better than the other, instead site context must be considered, in coordination with the military operational need and environmental impacts that are linked with each strategy.

2.9.1 Seawall



Hardened structures that make a delineated line between the sea and land. Built to withstand strong waves and storm surge, while protecting upland infrastructure from flooding.

Figure 8: *Seawall* (NYC Department of Planning 2013a)

Figure 9: *Seawall Foundation.* A massive foundation is required for structural stability (Bedford Carp Construction Inc. 2016).

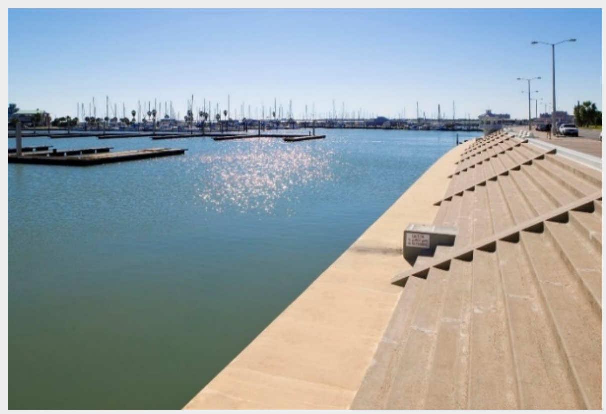


Figure 10: *Seawall Profile.* Seawalls have varying profiles; this example has a tiered section (HDR Inc. 2016).

Overview: Seawalls are hardened structures that are used all over the world to make a strong delineated line between the sea and land. They are typically used in locations where erosion is occurring or in areas where a deep seabed is required adjacent to land in order to support ships and mooring. The hardened structure protects valuable infrastructure inland against pounding waves and rising seas. Seawalls range in type and may include steel sheetpile walls, monolithic concrete barriers, rubble mound structures, brick or block walls or gabions (wire baskets filled with rocks) (Kamphuis 2000). They are inflexible in nature, heavily engineered; require extensive construction, and upfront financial investment. Seawall and armoring of all types prevents the natural retreat of the shoreline over time, causing passive erosion. Passive erosion results in the drowning of a beach in front of the structure while adjacent unarmored coastline migrates landward (Hall et al. 1991; Fletcher et al. 1997; Griggs 2005a,b).

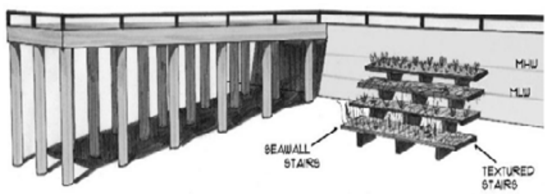
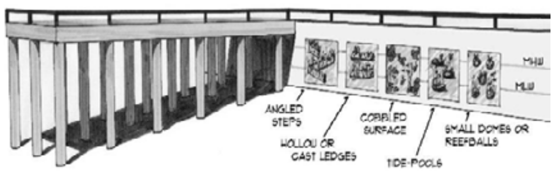
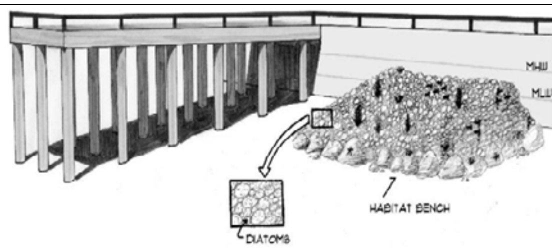
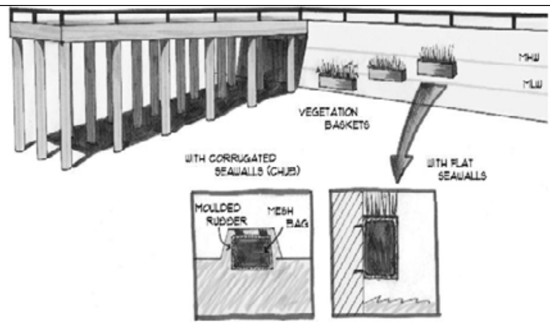
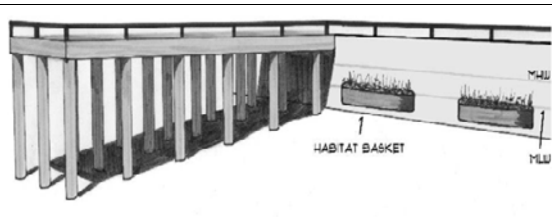
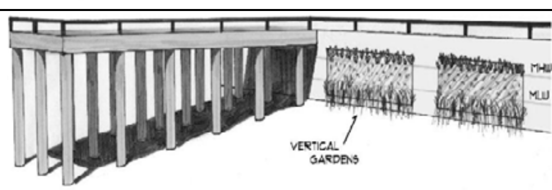
Benefits: Seawalls have relatively long lives, and can prevent autonomous coastal change (UN 1999). In a port type in environment, they provide a rigid structural frame, which allows for support utility services such as electrical and wastewater to be routed. The structural stability of the system allows piers to be built perpendicularly to the seawall, or allows mooring infrastructure to be placed directly on the seawall for parallel ship berthing. Allows for hardened service for movement of supplies from ship to shore and vice versa. Due to the nature of the Navy's mission, seawalls are vital for ship to shore transition.[8] Seawalls also have a much lower space requirement than other coastal defenses such as levees, especially if vertical seawall designs are selected. As well as fixing the boundary between land and sea, seawalls also provide coastal flood protection against extreme water levels. Provided they are appropriately designed to withstand the additional forces, seawalls will provide protection against water levels up to the seawall design height (Linham and Nicholls, 2016).

Concern: Microhabitat is present on rocky and natural shorelines, but is heavily modified or absent on conventional aquatic infrastructure. Two important types of microhabitat missing from seawalls are tide pools and crevices. On seawalls where microhabitat has been entirely removed, species diversity is significantly reduced (Bulleri et al. 2005; Chapman and Bulleri, 2003; Chapman 2006; Chapman and Bulleri 2003; Firth et al. 2013; Dyson and Yocom, 2014; Gacia, Paola, and Martin, 2007). Birds who forage along the shore can be greatly decreased with a lack of available food sources.

[8] Ship to shore in the context of the Navy means the ability to move goods and equipment from the shore to the ship, and inversely. Additionally the movement of several hundreds, to thousands of people in the context of an aircraft carrier, requires a safe brow and circulation zone for personnel. Ships while in port require power, water, and wastewater disposal; those utilities need a stable infrastructure platform.

Natural shorelines dissipate wave energy, versus causing large wave reverberations from seawalls (Langridge et al. 2014). Adjacent areas without armoring can erode, and due to alterations in wave patterns, the land may erode at a quicker rate in adjacent areas or the structure of the seawall can be undermined itself. The cumulative impact of multiple structures can result in significant impacts to aquatic ecosystems—including altered sediment accumulation and dispersal, creation of new barrier islands, and transformation of estuaries from tide-dominated to wave-dominated systems (Dyson and Yocom, 2014; Syvitski et al. 2005; Williams, Dellapenna, and Lee, 2013). Armoring with seawalls cannot be eliminated since it has very practical applications, but scientists and planners need to anticipate how armoring will affect other properties, and how further damage can be minimized (Dugan et al. 2008, Terchunian 1988). Lastly, older seawall structures designed prior to sea level rise projections must be upgraded for sea level rise scenarios, or there is great concern of overtopping and upland flooding.

Figure 11: Ecological Designs to Replace Traditional Seawalls
(Adapted From Dyson and Yocom, 2014)

	Illustration	Design Focus	Design successful	Key Resources
a. Seawall Stairs		-Reintroduce microhabitats including tidepools. - Increase intertidal habitat area. Reintroduce shallow water habitat for fish, vegetation, etc.	Yes; Vancouver Convention Center	Slogan, 2011 EBA, 2011
b. Seawall Texturing		- Reintroduce microhabitats including tidepools. - Create diverse surface orientations (horizontal, vertical, etc).	Yes; Seattle Seawall	Goff, 2008 Goff, 2010
c. Habitat Benches		- Increase intertidal habitat area. - Reintroduce shallow water habitat to benefit fish, vegetation, etc.	Yes; Olympic Sculpture Park in Seattle, WA	Toft et al., 2012 Toft et al., 2013
d. Vegetation Basket		- Create refuges for migrating fish, including juvenile fish. - Reintroduce shoreline vegetation.	No; plants died in trials in Cuyahoga River, OH	None in published literature.
e. Habitat Basket		- Reintroduce microhabitats including tidepools. - Reintroduce soft substrates, gravel, and cobble substrates.	No; waves washed sediment out of Seattle trial	Browne and Chapman, 2014
f. Vertical Garden		- Provide vegetative detritus for aquatic ecosystem. - Provide aesthetic waterfront experience.	Untried; although successful terrestrial examples exist	Francis and Lorimer, 2011

Case Example: Elliot Bay Seawall, Seattle, WA

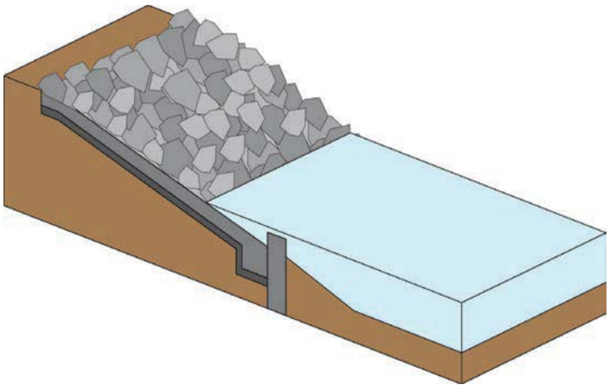
Seawalls are necessary to support port operations, and can serve as a resilient adaptation option to protect upland structure from sea level rise and storm surge. With the concern of habitat loss, there are innovative ways to preserve some ecological functions as demonstrated in the Elliot Bay Seawall. Over the past several decades new approaches—including ecological design—have emerged that seek to mitigate environmental impacts and recover neglected ecosystem services by integrating knowledge of ecosystem process and function into urban design practices (Dyson and Yocom, 2014).

Figure 12: *Seattle's Environmentally Friendly Seawall.* Seattle's seawall has portions of grates, which allows light to plant life below (City of Seattle 2016).

Section View: Seattle's seawall not only has habitat improvements incorporated into the design, but also is designed to be 2'10' above the mean high tide level, using the year 2100 sea level projections.

Innovation: Project incorporates materials and textures that mimic the physical properties of the natural habitats that support local native species. The texture and irregularities of surfaces allow for native plants and microorganism to attach to newly introduced structures (Dyson and Yocom, 2014; Lukens et al. 2004). Second, the ecological infrastructure design references locally specific and ecologically intact shorelines, paying particular attention to microhabitat, surface orientation, and nearshore habitat area (Dyson and Yocom, 2014; Chapman and Bulleri, 2003). The ability for marine plants to receive daylight, facilitating photosynthesis is critical, orientating some surfaces in a horizontal plane allows for denser marine plantings.

2.9.2 Revetments



Hardened structures made of stone or concrete geometric forms that reinforce the bank along the shoreline. Built to withstand pounding waves.

Figure 13: *Revetment* (NYC Department of Planning 2013a)

Figure 14: *Boulder Revetment.* No soft shoreline remains, although there is still water access (SNH 2016).

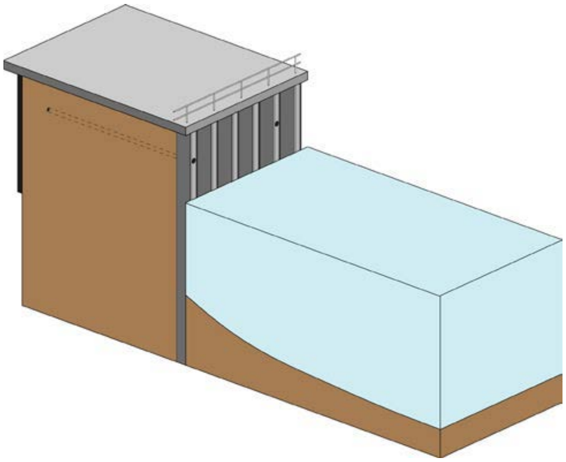
Figure 15: *Geometric Revetment.* Geometric concrete structures are an alternative to boulders (Freesteel Blog 2016).

Overview: Revetments are hardened structures that are used all over the world to make a strong delineated line between the sea and land. The hardened structure protects valuable infrastructure inland against pounding waves and storm surge. They are inflexible in nature, heavily engineered; require extensive construction, and upfront financial investment. Revetments similar to seawalls in the sense of providing shoreline protection from waves and retentions of soil, but instead are composed of large boulders, gabions, or concrete geo-structures. Revetments prevent the natural retreat of the shoreline over time, causing passive erosion if a beach was present during the installation of the structure. Passive erosion results in the drowning of a beach in front of the structure while adjacent unarmored coastline migrates landward (Hall and Pilkey 1991; Fletcher et al. 1997; Griggs 2005a,b).

Benefits: In the event of a major storm surge, they perform relatively well since they are in modular units, which are allowed to move and settle, unlike other fixed structural forms such as seawalls or bulkheads. They protect upland infrastructure from bank and shore erosion, due to slowly rising seas and small wave action. Although the intertidal zone is compromised primarily for bird habitat, some tidal marine life is able to adapt to the varying textures and surface orientation of the rocks. Ideal for locations that need a protective edge for upland infrastructure, but do not have the expansive space for a natural shoreline. Do allow limited human interaction with the water, for example in a park type setting, and based on aesthetic desires, natural plantings can be introduced to the structure.

Concerns: Similar to other shoreline hardening applications, it may disrupt sediment movement, starve beaches downdrift, and squeeze the beach in front of the structure. Armoring typically is built at 2:1 ratio, and results in mass loss of sandy beach or natural shoreline, Birds who forage in the sand can be greatly decreased with lack of shore (Dugan et al. 2008). Due to the built form, revetment are not suitable for maritime access. While seawalls and revetments may provide current protection for oceanfront development and infrastructure, they are usually designed for a particular set of wave and sea-level conditions. If sea level increases substantially and wave heights continue to increase, the original freeboard will be gradually exceeded, and overtopping will become more frequent (National Research Council 2012).

2.9.3 Bulkhead



Hardened structures that reinforce the bank along the shoreline to protect from coastal erosion.

Figure 16: *Bulkhead* (NYC Department of Planning 2013a)

Figure 17: *Sheet Vinyl Bulkhead.* Various materials can be used to form a bulkhead, this uses vinyl, and concrete (CMI 2014).

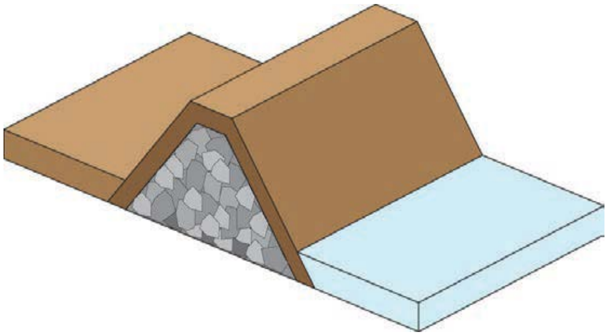
Figure 18: *Bulkhead Above Water Clearance.* Bulkheads are closer to the top of the water compared to a seawall (CMI 2014).

Overview: Bulkheads are often confused with seawalls, although they have similar uses, their resiliency and structural purpose differs. A bulkhead is placed at the toe of a bluff or instable piece of land, parallel to the shoreline to prevent the erosion of land or slope into the sea. They are designed to maintain soil stability, and standard wave action, but are not built to withstand severe storm surge or extreme rising sea levels. The "rule of thumb" in bulkhead design is to account for wave impacts if the significant wave height at a project site is expected to be in excess of three feet (MW Engineering 2014). They are typically constructed of steel pilings, timber wall pilings, timber crib reinforced with rock fill, or wire fencing with rock fill (USACE 2016a).

Benefits: Can prevent upland bank and shore erosion from slowly rising seas and small wave action. An alternative to seawalls, which are heavily reinforced, and expensive to construct. Bulkheads are more suitable to shorelines not impacted by continual pounding waves or frequent storm surge. Best suited for locations where space is in high demand or where water dependent uses, such as barge loading and unloading, require a steep vertical shoreline (NYC Department of Planning 2013a).

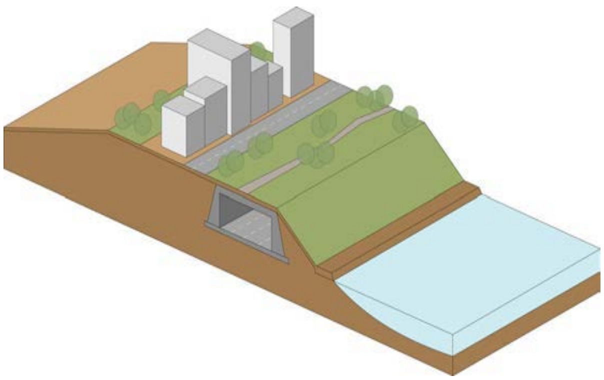
Concerns: Not constructed to protect against strong storm surge, or continual pounding waves. Similar to seawalls, in that they alter the shoreline biodiversity, and will not prevent the beach itself from eroding. In fact, bulkheads can cause increased erosion of the beach when waves reflect off the hard structure and erode nearby beaches (WA Department of Ecology 2016a).

2.9.4 Levees and Multipurpose Levees



Traditional levees are earth formed embankments that separate the sea or a river from the land, and built in order to prevent inland flooding.

Figure 19: *Traditional Levee* (NYC Department of Planning 2013a)



Multipurpose levees have the same characteristics as a traditional levee, but incorporate reinforced structure to support other infrastructure services.

Figure 20: *Multipurpose Levee* (NYC Department of Planning 2013a)

Figure 21: *Coastal Levee.* Traditional levees to be effective are typically very long structures (Coastal News Today 2016).

Figure 22: *Waterside Park Levee.* Within urban environments, can be incorporated into building or park structures (ANMC21 2016).

Overview: A levee is a manmade earthen structure to prevent a river flowing into adjacent land or infrastructure, or prevents ocean waves from overtopping and flooding. Levees are often used in areas where the ground elevation is at or below sea level. Levees widths and heights vary based on site-specific conditions, but in general, the height should consider the 100-year major storm event predictions, storm surge scenarios, as well as should project for sea level rise scenarios at least through 2100. They are better sited in inland coastal areas or at the mouth of rivers emptying to the sea, since they are designed to prevent flooding from water, but not protect from large wave patterns. Multi-purpose levees are often wider in nature to support embedded infrastructure or other built uses, this width can reduce the risk of overtopping.

Benefits: If designed appropriately for sea level rise scenarios, can protect valuable inland infrastructure from coastal flooding. Multi-purpose levees similar to a standard levee, but play additional roles, serving for example as a transportation spine, provide parking, support other miscellaneous structures or recreational activities that could benefit from being sited at a higher perspective.

Concerns: As demonstrated during Hurricane Katrina, levees can provide a false sense of security, and if required evacuation takes longer than expected. The major lesson is that hard infrastructure such as levees and floodwalls must be maintained and reinvested in. Even with those engineered strategies in place, nature can overcome, and additionally those engineered solutions often weaken the natural resilience of the shoreline (Scott 2006). Due to the conditions of inland infrastructure and land typically behind at or below sea level, other adaptation strategies should be employed to protect valuable infrastructure.

Case Example: Riverdike, Rotterdam

The city of Rotterdam has been exploring options to update their system of levees to account for sea level rise. Working with designers they have transformed the concept of a levee merely acting as a defensive structure, instead it is used an element within urban design for place making and utilitarian functions.

Innovation: Levees not only act as a protection against sea level rise, but also serve to raise the physical landscape along the shoreline, while serving as a foundation for adjacent facilities. Support infrastructure such as parking lots or temporary storage of goods can be housed in void spaces within the levee.

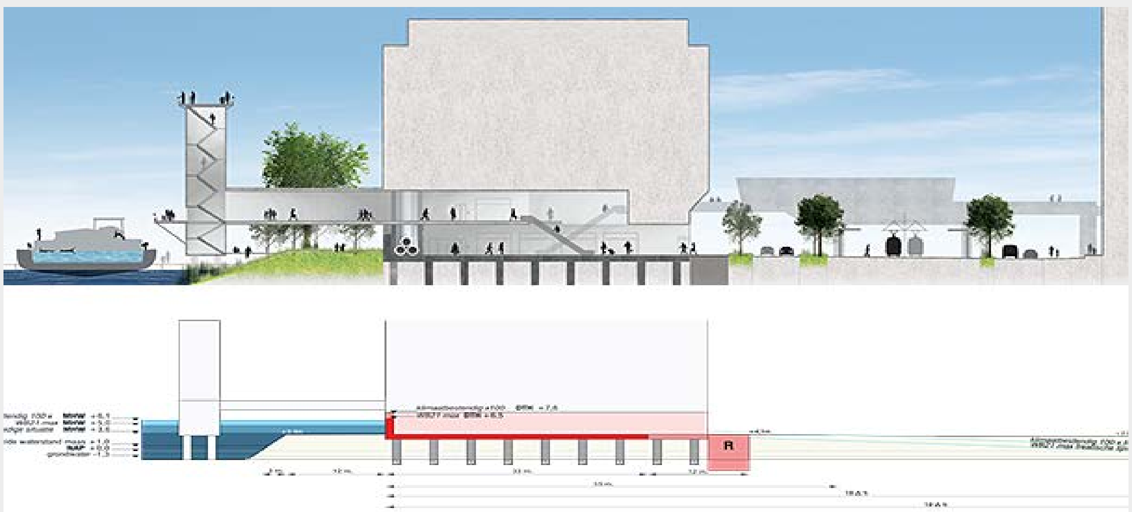
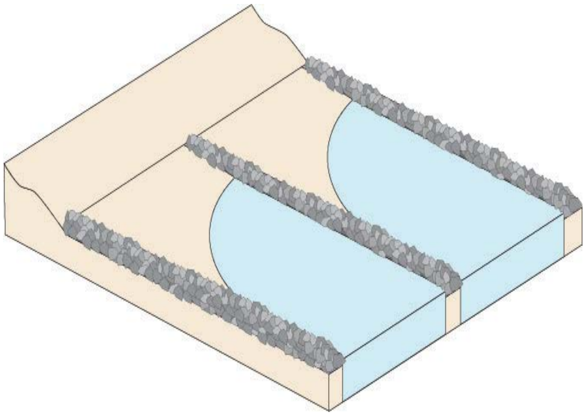


Figure 23: *Riverdike Section.* Section view shows how the adjacent foundation of a building can reinforce the levee (DE URBANISTEN 2016)

Figure 24: *Riverdike Perspective.* The mound itself is dual purposed as a transportation spine (DE URBANISTEN 2016)

2.9.5 Groins



Hardened structures perpendicular to the shoreline to protect against dominating tangential wave patterns. Built to withstand erosion that occurs by sand and sediment drift along the shoreline.

Figure 25: *Groins* (NYC Department of Planning 2013a)

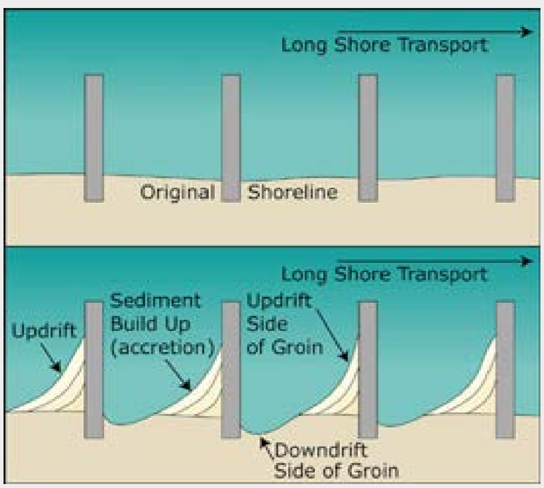


Figure 26: *Long Shore Transport*. After time, groins collect sediment in the updrift side of the groin, and the downdrift side erodes (North Carolina Coastal Federation 2016).

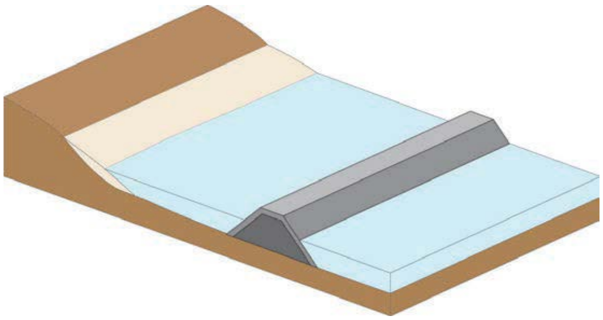
Figure 27: *Harbor Entry*. Groins are often used at the entry of a protected harbor or inland passage. They allow a strong delineated edge, which supports safe movement of ship and maritime traffic (Weebly 2016).

Overview: Groins are used to combat coastal erosion due to persistent wave patterns tangent to the shore and to lessen the shock of coastal storms upland from shore. They function as a physical barrier by intercepting sand moving along the shore. Sand is gradually trapped against the updrift side of the structure, resulting in a wider beach on this “supply-side” of the structure. However, on the downdrift side of the groin, the beach is deprived of natural replenishment of sediment (O’Brien 2014). They can be constructed with various materials including: concrete, stone, metal, or wood pilings. They serve to maintain a desirable channel for the purpose of flood control and ensure open marine lanes. They may be designed either as submerged or as non-submerged, are perpendicular to the coastline, and can be straight, t-head, l-shaped or hockey shaped (Dehghani et. al 2013).

Benefits: They are used to stabilize the opening of marinas, ports, and harbors. They can be used to protect inlets, where a defined shoreline or fall out from a river must be maintained. They are also strategically placed to prevent erosion in critical areas along soft shorelines, and are used in combination with a beach nourishment plan.

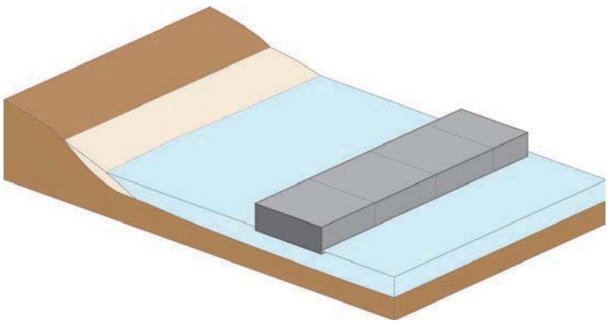
Concerns: Although they can lessen the shock of cross-shore erosion for the updrift side during a storm event due to a wider beach, the downdrift side has increased vulnerability due to the weakened resiliency and width of the beach. Beach nourishment can supplement the lack of material in a beach downdrift, if further erosion is a concern. In the case of groins placed near barrier islands, the unfettered flow of sand through natural inlets is an important mechanism maintaining barrier island health. Blocking this flow of sand will inhibit the ability of the barrier island to respond to rising sea level and storms (Pietrafesa 2012).

2.9.6 Breakwaters and Floating Breakwaters



Traditional breakwaters are hardened off shore structures typically made of stone or concrete that break strong waves away from shore, and allow dissipated waves to reach the shoreline.

Figure 28: *Traditional Breakwater* (NYC Department of Planning 2013a)



Floating breakwaters are hardened off shore structures typically made of reinforced concrete, logs, rubber or steel drums that are attached to piles driven into the sea. This allows the structure to rise and fall with the tide. They break waves away from shore, and allow dissipated waves to reach the shoreline.

Figure 29: *Floating Breakwater* (NYC Department of Planning 2013a)

Figure 30: *Breakwater Wave Patterns.* Water is choppy on the open water side, and calm within the breakwater (Panoramio 2013).

Figure 31: *Breakwaters Reverberating Waves.* Floating breakwater can move up and down with tide (Bellingham Marine.2016).

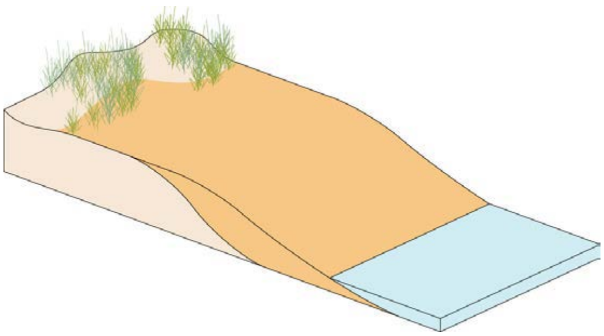
Overview: Breakwaters are hardened structures offshore that serve to reduce wave energy from hitting the shoreline, which ultimately protects against coastal erosion and can help weaken the intensity of storm surge. Typically placed parallel to the shore, strong ocean waves hit the structure, and are then dissipated into weaker waves that hit the shoreline. Since weakened waves are allowed to reach the shore, sediment and sand are allowed to collect along the shoreline. Traditional breakwaters due to the sheer size, and creating a physical wall within the ocean, perform better against large waves compared to floating breakwaters. Since typical breakwaters are fixed, new construction or maintenance efforts should consider sea level rise projections. Floating breakwaters are more flexible in nature since they rise and fall with the tide, and can provide flexibility for increased sea level rise. They are intended for waves, but only waves shorter in length and intensity, and are commonly used to protect against boats and marinas from waves and wakes (NYC Department of Planning 2013a).

Traditional breakwaters (emerged type) are designed to attenuate the whole wave action and are design to withstand the direct impact of a wave breaking, resulting in larger structures that often eliminate water circulation at the leeward side. If water circulation and environmental preservation is a strong consideration, then submerged breakwaters are an alternative. Submerged breakwaters are constructed at 40-50% of the water depth, and allowing overtopping and greater water circulation (Pinto, Neves, and Valente 2004). Submerged breakwaters do not protect to the same level as a traditional breakwater, so areas not subjected to large wave action or boating activity are better suited.

Benefits: Often used in conjunction with beach nourishment or natural shoreline projects. The hardened structure is removed from the shoreline, which allows the ecosystem functions to remain in place if currently present, or protects hardened infrastructure such as seawalls or bulkheads from increased wave action. Traditional breakwaters can served similar to artificial reefs, allowing marine life to collect and live within crevices of rock formations. Submerged breakwaters allow for better visual clarity, and increased water circulation.

Concerns: Fixed breakwaters during high tides or due to sea level rise can become submerged, causing concern for boating navigation. Additionally they can reduced water circulation, creating water quality concerns on the leeward side. Due to the constant exposure of waves, solid or vertical breakwater should not be placed in water deeper than 2 meters, and foundations must be of firm surfaces such as rock, stiff clay or coral reef in order to prevent structural damage (Sciortino 2010). Breakwaters do not prevent flooding or curb sea level rise, instead they are used to lessen the impacts of waves contributing to shoreline erosion.

2.9.7 Beach Nourishment



Shorelines provide a natural buffer for coastal waves and flooding. Sand along with native plantings are added to the shoreline to reinforce the natural structure.

Figure 32: *Beach Nourishment* (NYC Department of Planning 2013a)

Figure 33: *Raised Beach.* Large piles of sand recently deposited to raise the height of the beach (Woods Hole Group 2011).

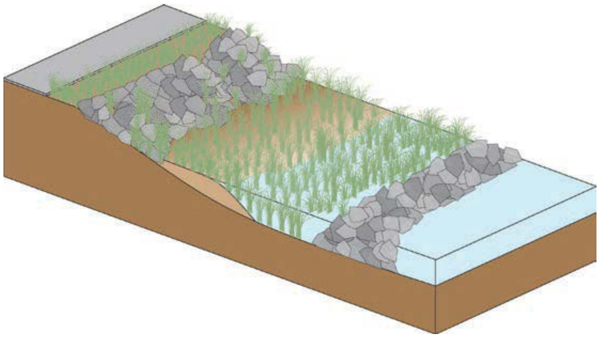
Figure 34: *Beach Nourishment in Process.* Sand is collected from a nearby ocean bed, and then sprayed onto shore (ESCP 2013).

Overview: Beach nourishment is seen as a "soft" protection method and an alternative to hardened infrastructure. This strategy is best suited for low-lying areas, that have an existing sand shore, and where additional sand for replenishment is available locally. Sand is placed on beaches to increase the elevation and distance between upland areas and shoreline, which acts as a buffer to dissipate storm wave energy and block rising water from inundating lower elevation areas (NYC Department of Planning 2013a). It is suitable for beaches that have traditionally low waves, and does not perform well where wave action is high in a sustained pattern. During intense storms, the sand is worn away, but this adaptation strategy is seen as a better alternative than erosion of upland habitat or infrastructure. Due to storm erosion, or based on gradual erosion that takes place over a longer time period, the beach will have to be renourished with additional sand. A beach nourishment project typically lasts between three and ten years depending on the site and number and intensity of storms (NOAA 2000). In addition to sand, geotextile tubes filled with sand can help stabilize the beach or planting native vegetation and grasses can help reinforce the beach, and keep sand intact longer. One alternative to a traditional single bermed beach, is to have multiple sand/vegetation berms. The first protects against crashing waves, and the second further in-land protects against coastal flooding.

Benefits: In traditional settings, recreation is maintained. In areas with upland infrastructure, beach nourishment is a more natural way of protecting the shoreline from waves, flooding, and erosion, while maintaining a significant distance between infrastructure and water during storm events. Dunes offer additional protection by strengthening the ability to dissipate waves and can offer additional height to protect from surge. Reinforced or "armored" dunes act as sand covered seawalls to protect from surge events and can withstand heavy wave action (NYC Department of Planning 2013a).

Concerns: Onshore, beach nourishment can disrupt species living, feeding, and nesting on the beach; offshore, beach nourishment can disturb habitat at the dredging site (Hanak and Moreno, 2012, Kriesel and Friedman, 2003). Beach nourishment is not a one-time effort, continual maintenance, and additional sand will have to be added periodically which can be costly.

2.9.8 Living Shoreline



Living shorelines address erosion in areas of lower waves, by dissipating wave patterns into strategically located vegetated shoreline habitats and incorporate ecological functions to better protect the shore.

Figure 35: *Living Shoreline* (NYC Department of Planning 2013a)

Figure 36: *Living Shoreline Habitat.* Native shoreline shrubs and grasses create great habitat for fish and aquatic animals (PA Times 2014).

Figure 37: *Combination Shoreline.* This shoreline uses a mix of boulders and grasses to reinforce the shoreline (NOAA 2015a).

Overview: This protective strategy is best suited for bays, estuaries, or wetlands, which have a flat transitional slope from shoreline to water. Living shoreline treatments address erosion in areas of lower waves, by dissipating wave patterns into strategically located vegetated shoreline habitats. They also can serve as a defense for low surge flooding (Hanak and Moreno, 2012). Plants, stones, and sand fill are used to naturally harden the shoreline, without fixed manmade structures that sever adjacencies of upland and aquatic areas. The benefits include a more natural appearance along the shore, increased habitat for birds and fish, water filtration, and recreation (Center for Coastal Resources Management 2016).

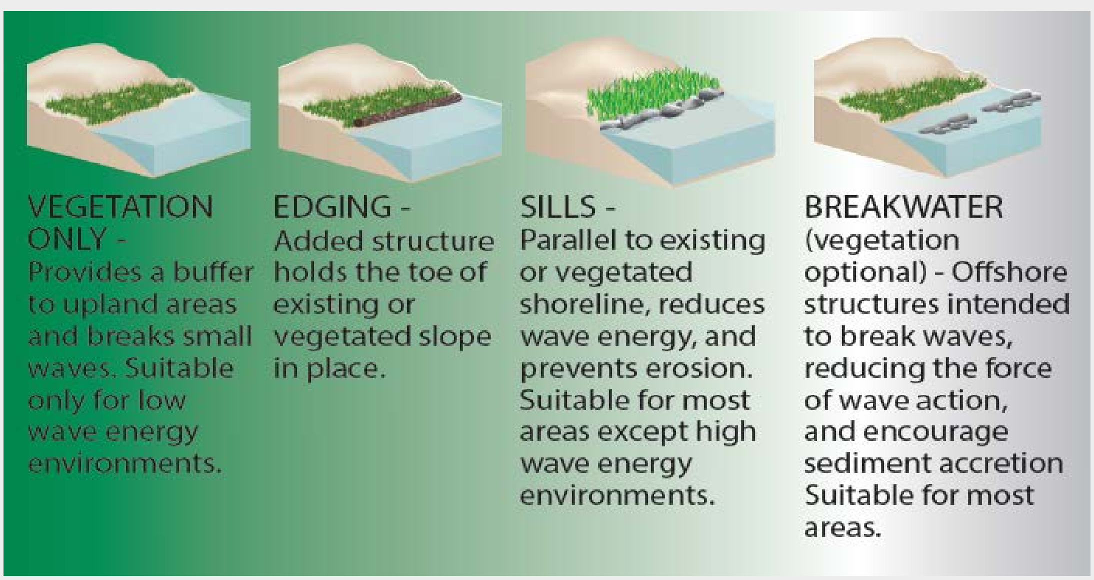
When assessing if a living shoreline is appropriate, coastal planners can use principles from ecosystem-based management (EBM) to coordinate this adaptation strategy with existing conditions. The key principles of ecosystem-based management include:

1. The ecosystem should be maintained in a desirable state to ensure no further damage is done. Improvement of damaged areas must be balanced, in order to not harm other adjacent or downstream ecosystems.
2. Management decisions have a safety factor, since nature is not always predictable.
3. Protect wild living resources while balancing the use of other resources.
4. Survey existing conditions thoroughly before any implementation of policy (Long, Charles, and Stephenson, 2015).

An alternative to a completely natural shoreline, is a hybrid living shoreline, in which living shoreline elements (plants, stone, and sand) are added to new or pre-existing hardened structures. Hybrid stabilization incorporates a created marsh in combination with a stabilizing structure such as a low profile stone sill, revetment, or breakwater.

Spectrum of Living Shoreline and Hybrid Options

Figure 38: NOAA 2015a



Benefits: Besides protecting shorelines from increased erosion, living shorelines improve localized water quality and the ecosystem. Many states on the east coast have enhanced their state regulations to encourage or require "living shorelines". Typically, these created marshlands are mature and producing similar benefits to natural marshlands within 5-15 years. Epifaunal animals (shell fish, star fish, things that attach their-self's to rock) often replace infaunal animals (clams or burrowing worms and crabs). It has to be determined if a new species is better than no animals at all within threatened coastal habitats (Bilkovic and Mitchell, 2013). Living shorelines are also a good strategy when a more natural look is desired, and can are less expensive than hardened structures.

Concerns: Not appropriate for areas with high-energy wave action or where a defined hardened edge is required. Living shorelines can be challenging to design since they require coastal engineers to coordinate extensively with scientist and ecologists; this extensive coordination is a principle of ecosystem-based management. Ecosystem-based management developed in the 1980's to look at ecosystems in a larger scale, and to not only place emphasis on human activity, but also equally the natural landscape and animals. Due to politics, ecosystem-based management's popularity has decreased in land-based ecosystem policy, but is still used in marine policy. Lack of evidence-based case studies is a hindrance to getting the process widely used and accepted (Wasson et al. 2015). Additionally natural shorelines need greater widths in order to protect inland structure, so they require more space than a bulkhead or typical revetment.

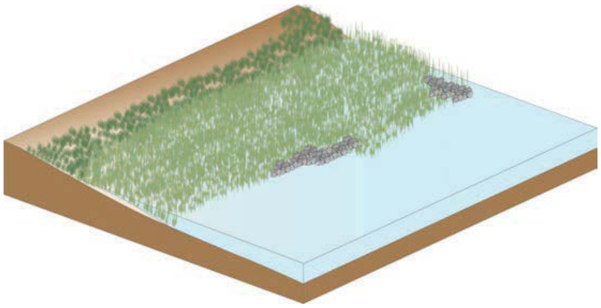
Case Example: Naval Support Activity Panama City, FL

Continued beach erosion was causing concern for the Naval Support Activity installation located on St. Andrew Bay. The bay is one of the last significant sea grass beds remaining in northwest Florida, and provides rich habitat for several aquatic species. Instead of choosing a traditional hardened method, such as a breakwater or revetment, the Navy chose a more environmentally friendly option by restoring three damaged segments (800', 900' and 1400' long) with living shorelines. Since erosion of shoreline can smother sea grass beds, which support local fish and other estuarine species, a living shoreline protects and enhances juvenile habitats and foraging grounds for fish (DOD 2011). The living shoreline protects against erosion, while also serving as natural filter for storm water runoff that reaches the bay

Innovation: Two-phased project included the addition of 175 oyster reefs from recycled local fish houses' shells. Second phase installed 22,000 salt marsh grasses, which were planted by Navy personnel and volunteers from the community.

Figure 39-42: *Naval Support Activity Panama City, FL Living Shoreline.* The shoreline before stabilization (top left), and the same area after grasses have taken root (middle). The project created a sense of community and environmental pride, by using local sailors, college students, and community members to plant the grasses (DOD 2011).

2.9.9 Constructed Wetlands



A constructed wetland is a newly built or restored wetland, that uses soil and natural plantings to filter water, create wildlife habitat, and serve as a buffer for coastal storm surge and inundation.

Figure 43: *Constructed Wetland* (NYC Department of Planning 2013a)

Figure 44: *Wetland Moving Boundaries.* Aerial view of the expanse of wetlands, and how they also support underwater ecosystems (WA State Department of Ecology 2016b).

Figure 45: *Multilayered Habitat.* Wetlands support a variety of plant types, and this example shows how they can naturally be near built infrastructure (Lochmueller Group 2016).

Overview: Wetlands are natural transitions from the water to upland areas, and occur where water covers the soil for all or most of the year. They consist of decomposing plant materials, plant species called hydrophytes (plants adapted to extended presence of water), and hydric soil which is characteristic to wetlands. They vary greatly from region to region, and can naturally occur in tidal and riparian zones. Wetlands provide valuable ecosystem services that include filtering pollutants from water and providing habitat for over one-third of the United States' threatened and endangered species. Wetlands play an integral role in the ecology of the watershed**.** The combination of shallow water, high levels of nutrients and primary productivity is ideal for the development of organisms that form the base of the food web and feed many species of fish, amphibians, shellfish, and insects (EPA 2016). They also act as a natural buffer from flooding and protect against erosion.

Constructed wetlands are ideally located in relatively flat tidal or riparian areas, as well as areas with low wave action, with low to medium currents. Constructed wetlands can be placed in areas of high energy, as long as they are combined with other adaptation strategies such as a breakwater. Restored coastal wetlands occurs on lands where vegetated wetlands once existed, but are now behind levees. Diking and drainage of coastal wetlands resulted in land subsidence, and as such these lands often require raising, usually through natural sedimentation. Restoration of degraded coastal wetlands offers a potential reverse to greenhouse gas emissions, enhances existing carbon stocks and enhances the original co-benefits of the wetland (Crooks et al. 2011).

Coastal watersheds as seen on the map below can extend many miles inland from the shore. The extent and condition of wetlands within a coastal watershed is both dependent on and influences the health of the surrounding watershed (EPA 2016).

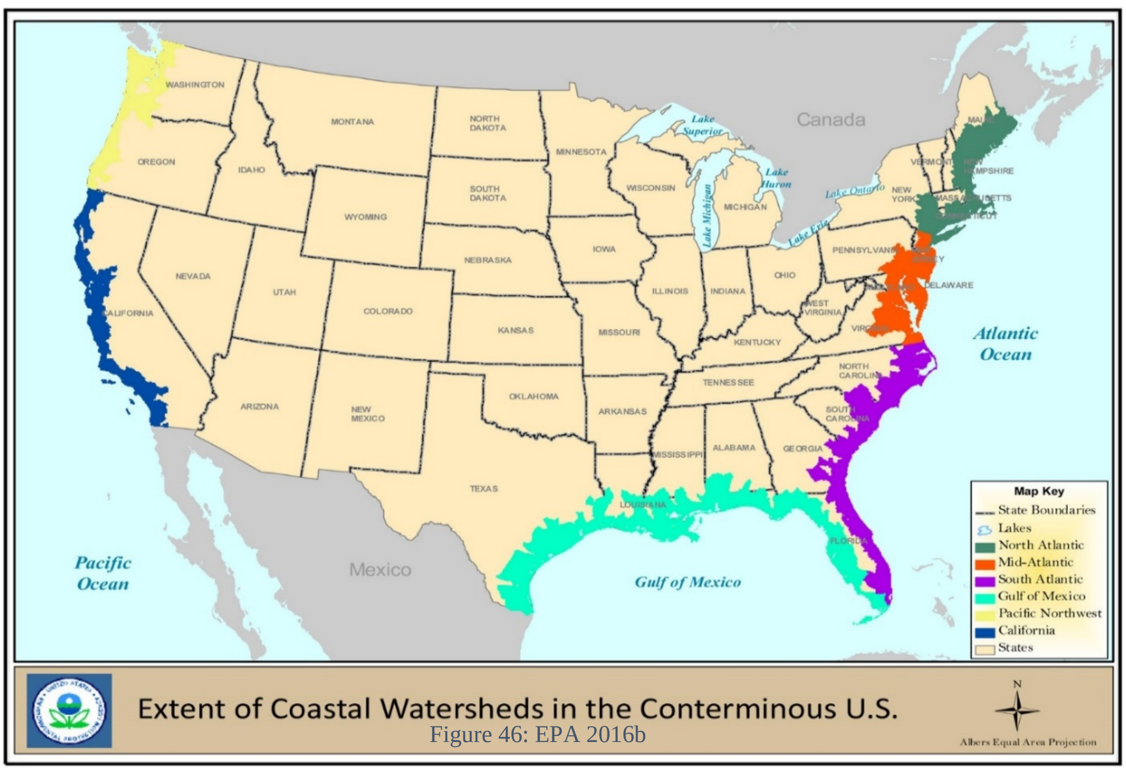


Figure 46: EPA 2016b

Benefits: Wetlands are often referred to as nature's sponge, as they trap and slowly release surface water, rain, snowmelt, groundwater and floodwaters. Trees, root mats and other wetland vegetation also slow the speed of flood waters and distribute them more slowly over the floodplain. This combined water storage and braking action lowers flood heights and reduces erosion (EPA 2016a). During coastal storm events, wetlands attenuate storm surge, help to dissipate waves, and slow surface winds down (Farber 1987; Wamsley et al. 2010). High attenuation across relatively small traverse distances suggests that even narrow wetlands offer relatively high shoreline erosion protection value (Barbier et al. 2008; Morgan, Burdick, and Short, 2009). Besides adaptive benefits that wetlands provide, they provide mitigation strategies also in the form of a carbon sink. Coastal wetlands and marine ecosystems hold vast stores of carbon. Occupying only 2% of seabed area, vegetated wetlands represent 50% of carbon transfer from oceans to sediments (Duarte, Middelburg, and Caraco, 2005).

Concerns: The success of constructed wetlands is highly dependent on the continuity of the wetland, and the existing shoreline conditions. Coordination with local ecologists and scientists is important to ensure the intended goals of the project are achieved. Additionally environmental impacts must be considered, the flattening of topography that may be required to create wetlands, as well as the placement of fill into open waters to create shallower areas for wetland vegetation to take hold, may have unintended flood impacts and adjacent habitat impacts that should be examined (NYC Department of Planning 2013a). In relation to sea level rise organic matter accumulation that naturally occurs in wetlands is limited by salinity and has a maximum threshold; freshwater wetlands are able to accrete at rates greater than sea level rise, until an elevation threshold relative to water elevations is reached (Crooks et al. 2011).

2.10 Accommodate

The strategy of accommodate proposes continued occupancy and use of vulnerable areas, but human actions change in response to sea level rise and water inundation (Dronkers et al. 1900). Change can occur by changing the building envelope, or by elevating a structure to allow water to flow beneath the structure. Accommodation acknowledges that the sea level is rising and floods will occur, but changes the way humans and the built form responds, instead of attempting to control the inundation as exemplified in protect strategies. Several accommodate actions can be viewed as an interim approach to adaption, for example individual buildings can be altered for increased resiliency against water intrusion in the short term, while alternate long term plans of relocating or building protective measures to protect large areas of land can be planned and implemented in the long term. Based on site conditions and sea level rise projections, accommodation may serve as a viable long-term adaption strategy.

2.10.1 Dry Floodproofing

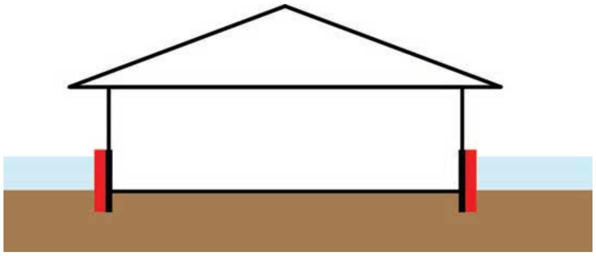


Figure 47: *Dry Floodproofing New Construction* (NYC Department of Planning 2013a)

New Construction: The building structure is designed to withstand water infiltration and loads. Exterior materials are water resistant and penetrations, including doors and windows are watertight.

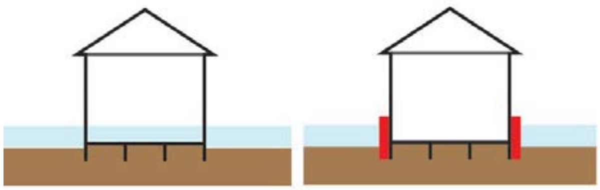


Figure 48: *Dry Floodproofing Existing Construction* (NYC Department of Planning 2013a)

Existing Construction: The building is retrofitted to seal all penetrations with water resistant materials and gates. Exterior walls and foundation may need to be reinforced to counter hydrostatic loads.

Figure 49: *Integrated Design.* Floodproofing was included into original design, so the system nicely blends with the architecture (NYC Department of Planning 2013a).

Figure 50: *Temporary Floodproofing.* Floodproofing is added before a storm, the system ties into pre-existing mounts and receivers (NYCEDC 2015).

Overview: The goal of floodproofing in both new and existing structures is to create a watertight enclosure, which prevents floodwater from intruding into the interior of a facility. The enclosure is made watertight by installing impermeable materials that are resistant to water on the exterior façade.

Designers must also ensure the physical structure is built in order to accommodate the hydrostatic pressure of water loads, and resist the uplift push of bouncy. The structure is not designed to account for large pounding waves, instead the gradual rise of floodwaters. Penetrations and seams are carefully sealed, and doors and windows are outfitted with floodgates typically made of sheet metal and rubber gaskets. Gates can be permanently in place, or deployable shields can be installed in the anticipation of a flood. Dry floodproofing is typically constructed for facilities that will receive no more than a 3-4 feet storm surge.

Dry floodproofing is constructed with the intent of ensuring that spaces at or below grade can be occupied. For residential purposes, FEMA and several states do not recommend or allow dry floodproofing per code due to the false sense of security it may create, which may lead to residents not evacuating when there is threat of a storm (NYC Department of Planning 2013a). Alternatively, it is a viable option for multi-storied mixed use, commercial, or community facilities. Due to the expense, it may not be viable for industrial type spaces due to the nature of large size and quantity of openings, but if combined with raising the pads of critical infrastructure within the industrial facility it increases the resiliency of the building as whole. Additionally if the entire facility cannot be retrofitted, then specific utility system and infrastructure can be dryproofed individually.

Benefits: Provides protection from storm surge and flooding waters that can damage valuable equipment and materials within a facility. Allows for the use of space at or below grade that typically would have been reserved for parking, access, or storage. Aesthetically most dry proofed structures blend into their surroundings, without a significant amount of focus on varying materials or structure until the floodgates are deployed. Floodgates can be chosen to look unassuming if incorporated into the design in the beginning, or deployable gates can be stored out of sight. This is an attractive option for facilities that have a public presence, and looks much less prominent than a standalone floodwall.

Concern: Dry floodproofing can create a false sense of security, and should be used in combination with sound interior design and elevation of critical assets within a facility, for example computer servers, critical data, and or electrical equipment should be elevated on mounts or pedestals if valued highly. With new, but especially with existing construction it can be very challenging to seal or block all penetrations into the foundation or exterior enclosure. Below grade spaces such as sidewalk vaults, electrical substations, basement-level mechanical, electrical, vertical transport, and fire protection equipment require consideration and protection (NYC Department of Planning 2013a). Wood and steel light frame structures do not have the structural integrity at their foundations or perimeter walls to withstand strong hydrostatic loads, so this application is better suited for multi-stored facilities that have reinforced foundations and walls typically constructed of concrete or reinforced masonry. Masonry is not completely impermeable by nature, and requires additional sealants comprised of asphalt-based or polymeric compounds that can be painted or sprayed onto the wall (FEMA 1986). While dry floodproofing can be incorporated into the normal construction schedule of a new facility, existing facilities will have to undergo extensive construction that may impede daily activities. The most invasive part of retrofitting a structure typically occurs with excavating around the perimeter of the facility to reinforce the foundation, seal joints, or during the installation of additional foundation drainage.

2.10.2 Wet Floodproofing

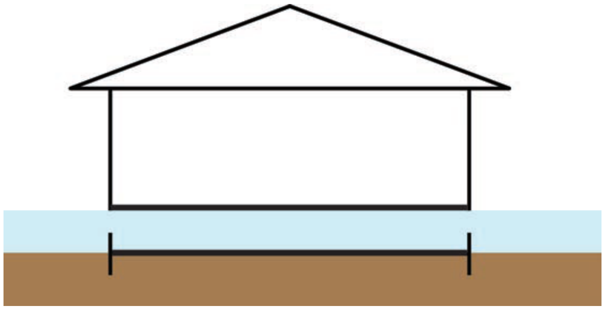


Figure 51: *Wet Floodproofing New Construction* (NYC Department of Planning 2013a)

New Construction: The first floor finished grade is built above the designed flood level. The void below allows free passage of water through vents, which allow the system's hydrostatic pressure to equalize. Materials are resistant to water damage.

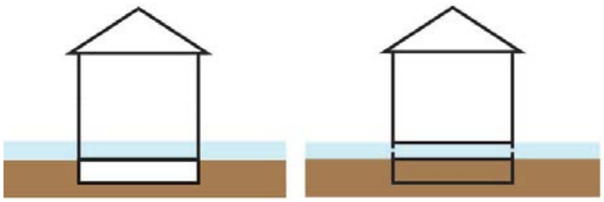


Figure 52: *Wet Floodproofing Existing Construction* (NYC Department of Planning 2013a)

Existing Construction: The building is retrofitted to allow water to flow through ground level spaces uninhabited. Finished spaces are raised above the designed flood level.

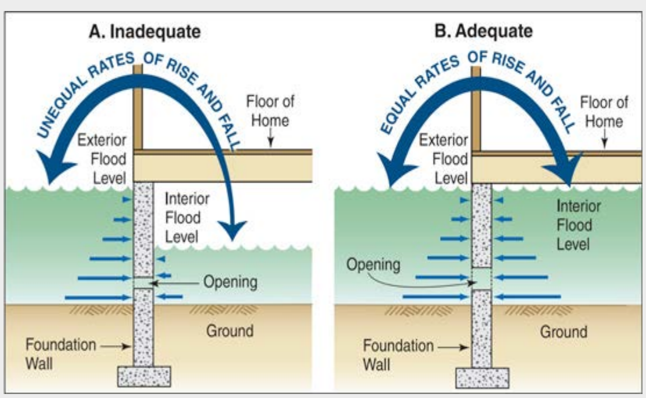


Figure 53: *Foundation Hydrostatic Pressure*. Graphic demonstrates the importance of installing the proper amount of openings to allow water to equalize on both sides of the foundation (MBM 2016).

Figure 54: *Foundation Screen*. Screen vent allows water to flow in both directions (MBM 2012).

Overview: Wet floodproofing has limited applications, and is intended for locations where there is concern of a structure being able to withstand the hydrostatic water pressure from a flood event. In those cases of structural concern, it is more effective to allow floodwaters to enter into designated uninhabited spaces through vents or preplaced holes in the foundation. The uninhabited space's materials are resistant to water damage, but if the space was used for storage, anything left in place will be damaged. That is why it is critical that any utilities or valuable equipment is moved from the space in anticipation of a storm or flood, and why living or working spaces are not allowed. Wet floodproofing is typically incorporated into residential or single story structures.

Benefits: This application is a viable option for garage or warehouse type spaces where valuable materials or equipment can be placed on overhead shelves, catwalks, or 2^{nd} level floors in anticipation of a flood. If adequate storage is not available onsite, then additional contents can be relocated offsite. With this option, equipment that cannot be moved (electrical and mechanical) should be placed on pedestals or hung. It is also a solution for light frame structures, which cannot endure large hydrostatic loads. Aesthetically wet floodproofing is very benign compared to dry floodproofing or elevating a structure, since from the exterior facade simple vents or foundation holes are the only visible aspect.

Concerns: Wet floodproofing is not intended to be a solution for long-term flooding. After Hurricane Katrina in 2005, FEMA officials noted great structural damage and mold presence for structures that were inundated with floodwater for sustained periods. Wooden structural members began to warp, plywood delaminated, and fiberboards began to deteriorate. The sooner the under structure was able to dry, the less damage was experienced (FEMA 2007). Wet proofing typically requires human action in the anticipation of a flood to relocate any valuable content, and will require humans to clean out debris and excess standing water after an event.

2.10.3 Elevate

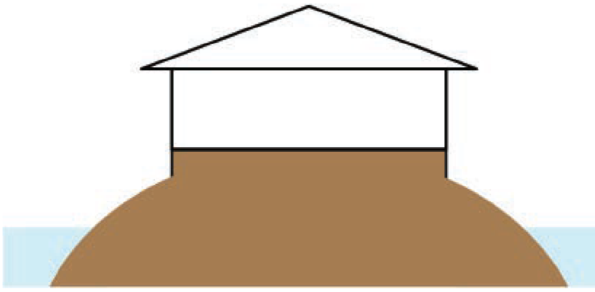


Figure 55: *Mound New Construction* (NYC Department of Planning 2013a)

Mound New Construction: Additional fill is added to the site, so the entire facility's structure will be placed above the flood and mean high water level.

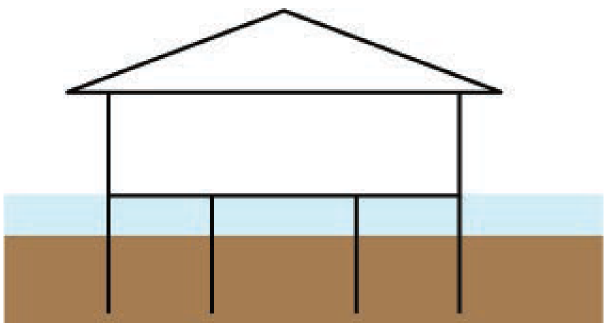


Figure 56: *Pier New Construction* (NYC Department of Planning 2013a)

Pier New Construction: The entire facility's structure is placed on columns or piers, so the final first floor level will be above designed flood height and mean high water level.

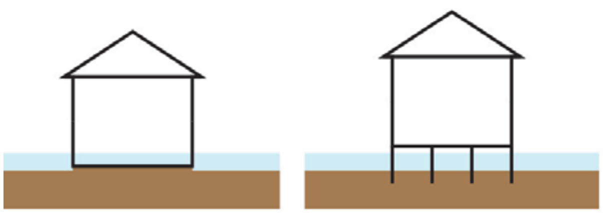


Figure 57: *Pier Existing Construction* (NYC Department of Planning 2013a)

Piers Existing Construction: The building is elevated with columns or piers so the final first floor level will be above designed flood height and mean high water level.

Figure 58: *Gradual Berm Elevation*. This facility is elevated on a gentle sloping berm, which also uses a revetment to protect the shoreline (SIMS 2016).

Figure 59: *Elevated Pier Foundation*. The facility is elevated on piers, allowing water to rise and flow under the first floor during a flood event (SCC 2016).

Overview: With the addition of fill to the site or regrading, the entire area surrounding the foundation of a facility is raised in order to accommodate the designed flood level, and can also be raised to accommodate future sea level rise and mean high tide levels. The designed flood level accounts for the base flood elevation (BFE) — The height of the base (1-percent annual chance or 100-year) flood in relation to the datum specified on the community's flood hazard map, usually the National Geodetic Vertical Datum of 1929 (NGVD), or the North American Vertical Datum of 1988 (NAVD) (FEMA 2008). If the site is large enough, plantings and gradual grades can make the transition from street level less dramatic. Structures that are newly built or are existing and raised on piers have the same concept of raising the structure above the threat of high water, but also allow the water to flow directly under the structure encase of a flood or storm surge. The open piers (along with lateral bracing) perform better against large ocean waves or fast moving currents, large mounds if not reinforced with plantings or rock can be subject to scouring from large waves.

Benefits: All habitable and storage spaces of the facility are located above the threat of water, ensuring preservation of life and property. This ensures minimal site cleanup after a storm event. For pier structures, parking or temporary storage can occur underneath the structure, and elevator cores are allowed below the design flood elevation if dry floodproofed (NYC Department of Planning 2013a), this is a viable facility structure for port type facilities, that need staging areas near the water, but also benefit from having administrative space near port operations.

Concerns: Major construction efforts are required in regrading a site, as well as driving piles, which requires specialized equipment and engineering to ensure soils have the bearing capacity. Based on the density of the area and actual site dimensions, grading may not be an option that fits within the context, or there may not be enough area to achieve the gradual height required for the mound without extensive retaining walls. In urban or dense areas, a building on piers may look out of place, and cause a lack of continuity on the street level. Special consideration must be made to consider ADA (Americans with Disabilities Act) in public facilities to ensure access.

Existing buildings that are retrofitted and raised on piers are typically residential or low-rise detached in nature. In general, large footprint, reinforced masonry, concrete structure, or those with a slab foundation are difficult to raise (FEMA 2007). Construction is very challenging, as the foundation is separated from the structure of the facility, and then the entire structure is elevated on hydraulic jacks. Foundation walls can be extended to the new structure height, or new piers/columns can be placed. With either option, considerations must be made on what will fill the newly formed void, and at a minimum wet floodproofing measures should take place.

Case Study: Sims Metal Management, Recycling Center, New York City, NY

The facility is the primary material recovery facility for all of New York City's curbside recycling. The design of the facility allows for float up barges to offload directly at grade into the processing center, reducing the amount of trucks and equipment moving materials around site.

Innovation: More than 5,000 tons of recycled glass aggregate was blended with 20,000 tons of mole rock to elevate sections of the 11 acre site by 4 feet. Buildings and equipment are protected against sea level rise and storm surge (SIMS 2016).

Figure 60: *SIMS Recycling Center*. (SIMS 2016).

2.10.4 Floodwalls

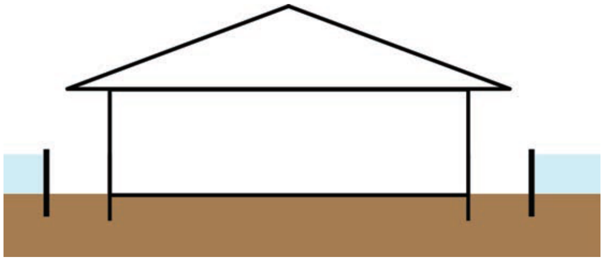


Figure 61: *Floodwalls* (NYC Department of Planning 2013a)

The use of permanent or removable floodwalls strategically placed around a site to counter occasional flooding and storm surge.

Figure 62: *Dual Purpose Floodwall.* This elaborate floodwall is design with the character of the complex, and also serves for security (The Environmental Agency 2012).

Figure 63: *Deployable Floodwall.* Floodwall that is deployed with the anticipation of a flood, maintenance personnel must ensure they know how to install (SCC 2016).

Overview: Floodwalls typically 1-20 feet tall are meant to counter periodic flood events or storm surge, and are strategically placed around the site of a building or complex of buildings to hold out rising waters. Some floodwalls are permanent in nature with reinforced brick our concrete materials, and can be built to coordinate with the landscape design of the site, other floodwalls are removable. Removable structures must have receiving structure in place around the site, so in the anticipation of a flood, panels can be taken from storage and placed into site. Although the system can protect the interior contents of a building, it does not count as a site protection measure for FEMA standards. The application of site or complex floodwalls should not be confused with levees, which also can incorporate walls.

Benefits: Floodwalls that are coordinated during the design process can be incorporated into the landscape design, and will blend into the overall aesthetic much better. Additionally they can be coordinated with the physical security of the site, and can serve to protect high valued facilities. Permanent structures also do not have to be installed in place by humans prior to an event, or stored on site, but they do require pop-up or mechanical gates to employ at site access points. If the system performs as intended, there will be no water or structural damage to the facility. Clean up around the immediate area of the facility is reduced after a storm. Due to robustness in materials for permanent floodwalls, they perform better against flood erosion compared to levees or berms placed around the site (FEMA 2007). Floodwalls also can be added to sites with preexisting buildings, and after installation, no additional floodproofing is required for the existing building.

Concerns: Floodwalls typically fail because of inability for a structure to withstand the sliding, overturning, or hydrostatic pressure of water (FEMA 2012). The more water the floodwall is designed to resist, the more robust the structure needs to be. This adds additional width and structure within the foundation of the system, which increases the physical size of the system on the site, plus adds substantial cost. Floodwalls that are removable must be stored in convenient and close location on site, plus facilities managers must rely on humans to act quickly to install the panels once a threat of flood or storm surge occurs. Ongoing training and accountability of the system should be considered. If used incorrectly, the system as a whole does little to keep out rising water. Depending on the robustness of the system, they can withstand some wave action, but are not intended to counter large ocean waves. Floodwalls can lead to a false sense of security, their intention is to preserve the interior contents of a building, not serve as a measure to let humans “wait it out”. Finally, the immediate site should not only be considered for flood damage, since local drainage patterns may be affected, possibly making worse conditions for other adjacent sites (FEMA 2007).

2.10.5 Floating Structures

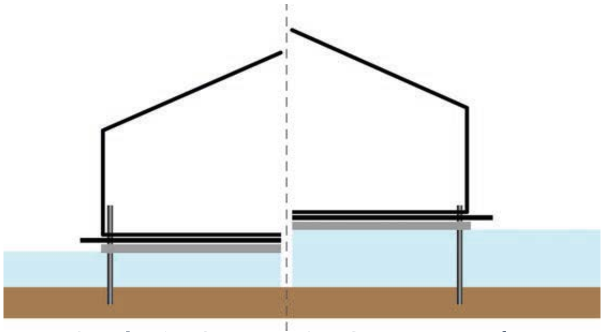


Figure 64: *Floating Structures* (NYC Department of Planning 2013a)

A floating structure floats on the water permanently, and rises and falls with the change of the tide.

Figure 65: *Floating Double-Deck Pier*. The Navy anticipates replacing some of their traditional piers, with floating double-deck piers (NAVFAC 2013).

Overview: Floating facilities are built on floating barges or pontoon systems that are anchored to piles or structurally adhered to mainland infrastructure. After placement, they are intended to remain in place. Floating structures can rise and fall with changes in tide conditions, and with adequate piles, can withstand storm surge levels as well. However, they require calm water sheltered from the ocean, major currents, and storm waves (NYC Department of Planning 2013a). Although typical floating structures today are primarily residential in nature, the technology in a port environment could be applied to piers, administrative support spaces, or temporary warehouse staging.

Benefits: The system can rise with sea level rise, and with adaptable transition connectors, shore based utilities can rise and fall with the system. Best suited for port type spaces that already have developed infrastructure along the shoreline. Additionally in areas of large tidal fluctuations, floating piers are able to rise and fall with berthed ships. A constant tidal level greatly simplifies cargo and supply transfer, mooring line handling, vessel fendering, and cable/hose routing between pier and ship. No dockside labor is needed for tending brows, mooring lines, and utility cables after berthing, as required for traditional piers (NAVFAC 2013). Due to the modularity of the system, the structure can be detached from the shore infrastructure, and relocated to another site encase of changing site conditions or fleet operational requirements.

Concerns: Floating structures are vulnerable to large waves, and should be placed in sheltered water bodies. Water based protection strategies such as groins or breakwaters can assist in stabilizing waves. Great scrutiny is applied in obtaining new permits for floating structures due to environmental concerns, but may be viable option for replacement of an existing pier structure that is beyond its service life. With any structure that is placed within the water, aquatic life may be harmed due to lack of light, and habitat loss.

Case Study: U.S. Navy Floating Double-Deck Pier

The U.S. Navy in coordination with BERGER/ABAM Engineers Inc. of Federal Way, Washington has designed, constructed, and tested since 2004 a modular hybrid pier. The Modular Hybrid Pier was conceived as a replacement for obsolete and deteriorating naval berthing facilities. Designed for 100 years of repair-free service, the pier will provide a high level of support services to a variety of vessel classes and facilitate a rapid upgrade of vessel utilities with the advance of fleet support system technologies (Lanier et al. 2005). The structure consists of high strength light weight concrete, floats entirely on top of the water with no structural support below, and is created in modules allowing flexibility and relocation to other sites based on Navy needs.

Innovation:

The modular pier has two accessible decks. The top deck will be used for ship to shore activities. The bottom deck will house utility systems, including shore power and water. Separating utilities from cargo handling improves operational efficiency and is a safer work environment. Since it floats it can rise with the sea level, and remains at a consistent height in relation to berthed ships.

Figure 66: *Flexible Utility Connections*. Hoses and utilities are linked to the pier with flexible connectors (Berger ABAM 2016).
Figure 67: *Multiple Circulation Decks.* Double-deck allow circulation on both levels of the deck (Berger ABAM 2016).

2.10.6 Planning Regulations and Tools

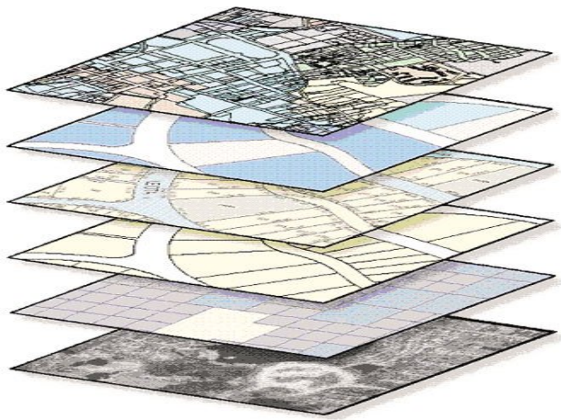


Figure 68: *Land Use Plan* (PMM 2015)

Planning regulations create a framework to organize development in coordination with community resiliency goals, while also taking into consideration the environment and safety of humans.

Planning Tools

Coastal adaptation is an ongoing process that requires planners to create a vision of resiliency, and tangible steps and goals in order to achieve incremental increases in coastal resiliency.

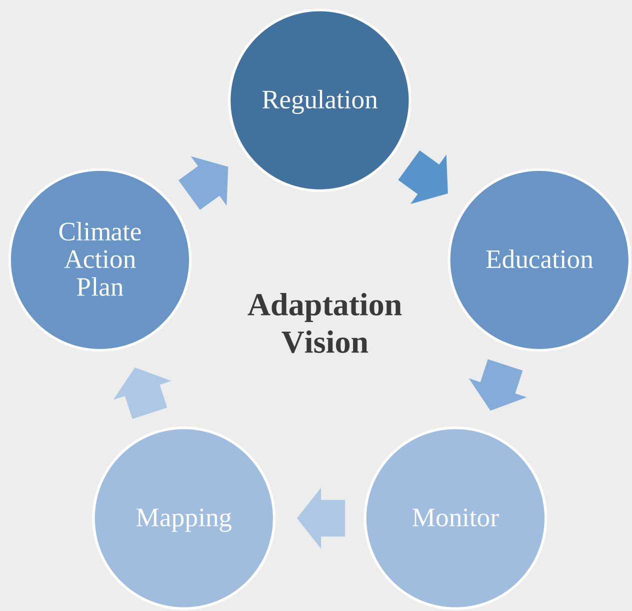


Figure 69: (Caponigro 2017)

Overview: Coastal planners are being asked to solve more complex problems everyday related to sea level rise, storm surge, and flooding, and when creating policy to counter these threats they must look at the holistic value of the shoreline. A vision for coastal adaptation must first be created by local planning staff, once that vision is created, coastal planners have a variety of tools to reinforce the effort. Mitigation and adaptation is not only achieved by building practices, but is also achieved by knowledge gathering and sharing, and by enforcing sound policies and land use regulations. Human health, environmental resiliency, military operations, or community economics must be considered in vision development, and for a resilient community all factors must be balanced.

The value of economics and shoreline protection are not necessarily a linear relation. Shorelines are valued for not only for port activities, tourism or resource extraction, but should also be valued for the water purification, natural protection, and varied habitats they provide. Function, economics, and the structure of the ecosystem must be evaluated first, so then a balanced decision can be made for coastal adaptation (Barbier et al 2008). Those decisions must weigh preservation of nature, while ensuring that economic and operational requirements are met.

Regulations and Tools Applied:

-Education: Understand the operational and cultural systems within the installation or community. Engage stakeholders, and understand their relationship with the shoreline, facilities, and what functional requirements do they have. Resiliency strategies should be integrated with existing norms and services (McGregor, Roberts, and Cousins, 2013). Education is a two-way process, stakeholders need to understand the threats of sea level rise, storm surge, and flooding, so they too can prepare and adapt their operations in response.

-Monitor: Monitoring changes in sea level, flood patterns, or storm patterns can help prioritize future investment in utilities, facilities, and direct where additional development is not advisable.

-Flood Mapping: Ensure flood mapping is up to date, and demonstrates 100 year and 500 year flood plains[9]. NOAA and/or the DOD Sea Level Rise (SLR) and Extreme Water Level (EWL) Scenario

[9] Flood hazard areas identified on the Flood Insurance Rate Map are identified as a Special Flood Hazard Area (SFHA). SFHA are defined as the area that will be inundated by the flood event having a 1-percent chance of being

website can be utilitized to project sea level rise scenarios, and can combine that threat with flood mapping. Vulnerable facilities, transportation corridors, utilities, and emergency service providers should be located on maps to demonstrate strengths or weakness, and resulting priorities in investment.

-Climate Adaptation Plan: Although climate change is a worldwide problem, it manifests itself differently in each region and site. Coastal planners should develop a site-specific climate adaptation plan that summarizes the risks, vulnerability, known information and potential measures for adaptation both physically and operationally. In order for communities to feel a sense of ownership of the problem, there are four basic principles that should be applied related to climate change adaptation plans: empower local leadership, provide efficient financing, promote citizen participation, and encourage jurisdictional coordination (McGregor, Roberts, and Cousins, 2013).

-Establish Policy and Regulation Tools: Once risk and vulnerability are identified, defined policy must be established not only to direct the planning department's agenda on adaptation, but also to create a framework for new buildings and projects to be evaluated against. Strategies below are listed in order of their ability to influence adaptation and coastal planning policy.

Land Use Regulations-The installation or city is broken down into land use types and should limit development in areas at risk, minimizing the potential for loss of life and property during hazardous events. Land use plans suggest comprehensive adjustments that include the location as well as the design of new development (Duarte, Middelburg, and Caraco, 2005). Land use plans indicate the most appropriate type of use on the land, for example, commercial, industrial, residential, agricultural, or protected type uses. Land use classifications will pair with zoning

equaled or exceeded in any given year. The 1-percent annual chance flood is also referred to as the base flood or 100-year flood. A 500-year flood has a 0.2-percent-annual-chance (FEMA 2016d).

regulations to control the density of structures or activity that can take place within a designated area.

Zoning- A tool used by governments that influences the use, bulk, and density of development in an area in order to achieve local planning objectives. Zoning amendments can facilitate investment in flood-resilient buildings by removing zoning disincentives to meeting or exceeding floodproofing standards in building codes (NYC Department of Planning 2013a). A critical element of zoning along the shore, is creating building setbacks from the mean high tide water mark. This setback should consider sea level rise, and observed/predicted storm surge levels. Removing a structure from the inundation zone is one of the best ways to create resiliency.

Building Codes-Are sets of regulations governing the design, construction, alteration, and maintenance of structures. They specify the minimum requirements to adequately safeguard the health, safety, and welfare of building occupants (FEMA 2016a). Building codes vary state to state, while the International Building Code is the most prevalent among the states, the Uniformed Building Code is followed by the United States Department of Defense. Besides building codes that regulate the structural aspects of a building, there are electric, mechanical, fire, and life safety codes that regulate those disciplines. Each city, county, or military branch can also include their own specific codes that regulate design and construction above and beyond the adopted codes, and can be tailored to include higher standards for sea level rise, storm surge, or flood prevention.

Benefits: A strong vision and commitment to sea level rise, storm surge, and coastal flooding adaptation will create clear guiding principles for a planning department. Staff will feel empowered to make decisions, allot resources, and secure funding when they know their decisions support the overall vision of the community, planning department, and leadership. Defined land use, zoning, and building codes create clarity for planning staff, while also demonstrating the exact parameters developers and stakeholders must follow when constructing new facilities or infrastructure. Defined regulations reduce the amount of personal opinion planning staff must use when making decisions, and instead they can rely on approved regulations to fulfill the decision making process. Lastly, a strong planning vision, coupled with knowledge gathering, allows coastal planners to prioritize adaption options to make existing facilities and infrastructure more resilient.

Concerns: Building codes and structural protection-the conventional approaches to hazard mitigation-have three weaknesses that have led a number of observers to conclude that more attention should be paid to limiting development in areas at risk from natural hazards through land use and zoning regulations (Advisory Committee on the International Decade for Natural Hazard Reduction, 1989).

Weaknesses of Building Codes-

1. Whenever development is allowed in hazardous areas, there is fundamentally risk of loss by the nature of just being in a hazardous area.
2. Although building codes increase structural and life safety, there are still adverse consequences of design limitations that stem from the fact that structural measures actually stimulate development in hazardous areas. Additionally building codes cannot "design out" all risk to a structure in an inherently vulnerable area.
3. Structural adjustments do little to protect and may actually harm environmentally sensitive areas such as ocean beaches, steep slopes, and wetland areas (Duarte, Middelburg, and Caraco, 2005).

Other concerns of planning regulations and tools stem from complacency. Sea level rise, storm surge, and flooding are dynamic, and planners must ensure they are periodically reviewing their vision and regulations to ensure they are relevant to existing built and operational conditions on the ground.

2.10.7 Essential Systems and Equipment Assessment and Action

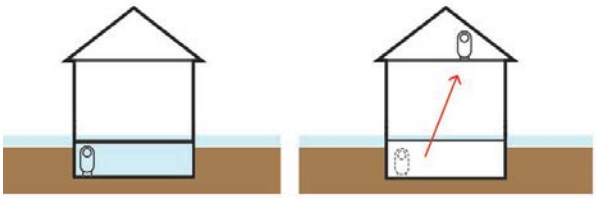


Figure 70: *Essential Systems Assessment* (NYC Department of Planning 2013a)

Increase resiliency by assessing essential systems, equipment, auxiliary parts, and the codependency of these systems. Strategic measures are then implemented to reduce exposure to risk.

Figure 71: *Naval Station Norfolk*. The largest naval installation in the world, is threatened by rising sea levels, and has a large web of utilities and infrastructure that are vulnerable unless they adapt. Short-term efforts can be done to increase resiliency by first adapting essential equipment (CNIC 2016b).

Overview: Essential systems and equipment are the backbone to all facilities, and allow facilities to operate as intended, including provisions for electricity, water, heating, cooling, plumbing, security, and communications. Human life, health, and comfort, as well as operational and business continuity are dependent on the coordination of these systems. Prior to any strategy for climate change adaptation, facility managers must first understand how these essential systems operate and inventory all the primary and ancillary equipment that is required for operation. Major components of essential systems and equipment are often placed on the lowest floors or subgrade (basement) levels in buildings. In some cases, equipment is installed on lower floors because of physical dimensions, the physical weight, or policy mandates (FEMA 2013). Investigating these spaces first when considering sea level rise or coastal flooding is a good initial step in analyzing risk, and then analyzing the codependency of essential services will aid in creating a priority list on what to adapt first.

See below for a list of essential services found on all naval installations, how those services are codependent with other services, and how climate change threatens their performance.

Table 3: Summary Chart of Vulnerability to Essential Systems
(Caponigro 2017)

Essential Systems	System Components	Service Importance and Essential System Codependency	Climate Change Threat
Electrical Systems	Primary Power Generator Power Transmission Lines Distribution Lines Switchgear Transformers DDC	Almost every other essential service has some requirement for electricity for proper performance. The electrical grid is a vast system of transmission and distribution lines, those lines voltages are powered up and down at substations who house transformers. Operators monitor flows over transmission lines, and balance generation and distribution. It is vital that information technology not only accurately demonstrates system demand or emergencies, but it is also critical that the information remains secure on the internet. Water is vital to cool power plants.	Power plants have high cooling requirements, and tend to be sited near coasts or large river floodplains. Sea Level Rise or flooding has the threat of inundating power plants, underground vaults, transformers, and substations (Rosenzweig et al. 2011). If water availability is threatened due to a man-made disaster or natural disaster like drought, then power plant operations can be threatened (McGregor et al. 2013). Changes in the frequency and severity of storms and other extreme events may also damage overhead energy infrastructure, resulting in energy shortages (EPA 2016c).
Water Systems	Domestic Water Sanitary Sewer Sump Pumps Stormwater Systems	Potable water is vital for human health and sanitation. Sanitary and stormwater systems collect respective waste water and distribute them to treatment plants or off site locations. Pumps require electric power to operate.	With increased flooding due to coastal storm surge or inundation from sea level rise, sanitary and stormwater systems can become overwhelmed. (McGregor et al. 2013). Standing water has the risk of flooding electrical vaults and distribution systems. Water availability is threatened with increased drought and higher temperatures, since water is diverted for electricity production (Rosenzweig et al. 2011).

Table 3: Summary Chart of Vulnerability to Essential Systems (Continued)			
Essential Systems	**System Components**	**Service Importance and Essential System Codependency**	**Climate Change Threat**
Mechanical Systems	Heating, Venting, Air Condition (HVAC)	HVAC is critical to heat, cool, and promote proper exchange within a facility. Electricity or natural gas is vital to HVAC equipment operation, as well as chilled water. Facilities that house IT equipment and other specialized equipment require cool temperature controlled spaces.	HVAC equipment is large and often placed on the ground floor, making it vulnerable to sea level rise and flooding. Increased storm surge and winds can damage HVAC equipment that is placed on roofs or outside. Increased heat and/or humidity is dangerous to human health and places a greater demand on HVAC equipment, also requiring additional energy for performance (McGregor et al. 2013, Rosenzweig et al. 2011).
	Plumbing		
Conveyance Systems	Elevators	Elevators and/or escalators are necessary and required per code in multistory facilities. They require electrical power to operate control systems, belts and pumps.	Sea level rise and flooding are a threat to elevator pits which are at or below ground level routinely. Elevator pits or rooms house the majority of pumps and equipment.
	Escalators		
Fuel Systems	Fuel Pumps	Fuel is required for not only mobile transportation, but also specialized services such as air and ship mobility. Natural gas and other specialized gases are required for heating, and specialized equipment used in medical procedures for example. Pumps require electric power, and any fuel stored indoors needs mechanical ventilation.	Fuel storage and distribution equipment is large and often placed on/or below ground, making it vulnerable to sea level rise and flooding. Flooding or storm surge events can cause fuel tanks to shift from their foundation (Rosenzweig et al. 2011)
	Lines		
	Tanks/Cylinders		
Communication Systems	Land-Based Phones	Telecommunications provides a technological foundation for societal communications. Communication plays a central role in the fundamental operations of a society—from business to government to families. In fact, communication among people is the essence of what distinguishes an organization, community, or society from a collection of individuals (Lucky and Eisenberg, 2006). Communication systems are depend on electricity for their network operations.	Climate change is expected to create more frequents and violent coastal storm events, communication systems are vital to communicate prior, during, and after a storm event to coordinate safety, response, and recovery efforts (FEMA 2013, Rosenzweig et al. 2011).
	Cellular		
	Radio		
	Transmitter		
	Receiver		

Table 3: Summary Chart of Vulnerability to Essential Systems (Continued)

Essential Systems	System Components	Service Importance and Essential System Codependency	Climate Change Threat
Data Systems	IT Servers	IT servers and networks not only serve the internet, but also facilitate closed networks the government and private industry use to manage operations, communicate, and manage utilities. Power is vital to operating IT systems, and conversely IT is used to monitor and control other utilities such as electricity, water, mechanical, specialized systems, and life safety monitoring.	IT servers and networks are housed in facilities, it is vital that those spaces maintain a constant cool temperature because of the potential heat load from the equipment and outside air temperatures. Server rooms are often located on the first floor of a building, making the system vulnerable to sea level rise and flooding.
	Networks		
	Wiring		
Security Systems	Cameras	Gates, pop-up barriers, and electronic security all require power. If those primary sources of power are disrupted, the physical security of any secure site/facility can be taken out unless there are emergency back-up generators.	Security system equipment that is located on/or below ground level is vulnerable to sea level rise and flooding. Pop up barriers or gates often have underground mechanism and power sources, water intrusion is a threat.
	Automatic Gates/Barriers		
	Intrusion Detection		
Specialized Equipment	Medical Diagnostic Equipment	Hospitals are a critical facilities within the community, and are required to perform a multitude of services that depend on highly regulated equipment. Ensuring medical equipment has access to uninterrupted power is required per code, and can be the difference between life and death. Varying rooms, especially surgical rooms require very particular HVAC performance. The safe distribution of potable and wastewater is required for patient/staff health. Data, communication, and security is vital for day to day operations (ASHE 2015, NFPA 2012).	Hospitals require not only primary power, but also back up generator power on site (ASHE 2015, NFPA 2012). They additionally have large HVAC plants which are often located on ground level or stand alone facilities. Careful consideration should be made for location of generators, ensuring they are not vulnerable to sea level rise or flooding. During coastal storm events, public safety is threatened, hospitals are critical in providing emergency services in response.
	Medical Gases		
	Medical Air		
	Medical Monitoring Equipment		
Life-Safety Equipment	Fire Alarm	Life-Safety equipment ensures the proper prevention, monitoring, and response to a fire. They ensure proper egress during an emergency event. The system is linked to data and communication systems the rely emergency events to emergency responders. Electrical power serves the life safety elements. Potable water and plumbing is required to serve sprinkler systems (NFPA 101).	Life-Safety equipment that is located on/or below ground level is vulnerable to sea level rise and coastal flooding.
	Fire Pumps		
	Sprinkler Systems		
	Smoke Control		

There are numerous options available to adapt essential systems and equipment, each strategy must be viewed relevant to localized threat, localized mission, and existing infrastructure, the strategies below are a consolidated list of viable options. Based on site analysis and differing factors (operational, environmental, and financial) each strategy has its own merit.

Equipment Specific Adaptation Strategies:

Floodproof Enclosures- The actual facility, room, or a constructed enclosure can be dry floodproofed. Dry floodproofing involves constructing flood barriers or shields around individual pieces of equipment or areas that contain essential equipment to prevent floodwaters from coming into contact with critical equipment. To work as intended, the barrier must be high enough to protect equipment from floodwater, strong enough to resist flood forces, and sealed well enough to control leakage and infiltration (FEMA 2013). The enclosure is made watertight by installing impermeable materials that are resistant to water on the exterior façade. Penetrations and seams are carefully sealed, and doors and windows are outfitted with floodgates typically made of sheet metal and rubber joints. Designers must also ensure the physical structure is built in order to accommodate the hydrostatic pressure of water loads, and resist the uplift pull of bouncy.

Image 72: *Backup Generators.* Located in a floodproof facility and are elevated off the ground (Johns Hopkins Medicine 2016).

Image 73: *Temporary Flood Barrier.* A worker is installing a flood barrier to protect an electrical room in anticipation of a storm (Flood Control America 2016).

Elevate- One of the most effective method to protect essential services is to elevate all essential and ancillary equipment. It should be placed above the highest anticipated flood elevation, or the elevation of the 0.2-percent-annual-chance flood recommended by FEMA, whichever is higher (FEMA 2013). If space is not available within existing first floor mechanical rooms, or if the equipment is below grade, then alternative locations within the facility must be found. This can present challenges since facility space it typically already utilized. Some equipment may be elevated to rooftops or attic type spaces. To elevate, the equipment can be hung, or may be placed on a secured pedestal. If the system cannot be elevated, then dry floodproofing may be an alternative option.

Seal External Utilities- Backflow valves are a measure to ensure sewer systems do not flow backward through drains and toilets during a flood. Access panels to vaults or underground utilities should have a neoprene gasket applied between the access cover and its seat. This combination should ensure a watertight seal. Pipe penetrations through an external wall can be sealed using an expansive sealant, a molded sleeve, an elastomeric seal, or a neoprene seal (FEMA 1999). Lateral outside penetrations should also be sealed to prevent water entering back through the pipe itself.

Anchor- Major floods or storm surge produce large currents, waves, or hydrostatic pressure that can shift heavy infrastructure, including fuel tanks. Ensure proper water resistant anchoring to adjacent structure or foundation. Underground tanks can shift also due to hydrostatic pressure.

Ground Fault Circuit Interrupters- If receptacle, outlets, or switches remain below the designed flood height, place these items on another circuit with ground fault circuit interrupter breakers to prevent electric shock.

Redundancy- As demonstrated in Table 3 above, electricity is integral to most other essential systems. To prevent complete loss of other services during an electrical outage, ensure backup generators are available to carry facility loads. A backup generator can either be permanently on site, and already hard wired into the facilities electrical grid, or emergency generators can be rented and brought to site in predetermined locations that have generators hookups and are not vulnerable to standing water or flooding. Permanent backup generators should be customary in critical facilities that require no service interruption. They should be placed on site where they are not vulnerable to flooding, and/or have their own floodproof walls. Emergency backup generators need to be tested periodically to ensure they perform properly, and that all support equipment (switchgear, fuel tanks, etc.) are also operating as intended.

Housekeeping- When emergencies or disasters occur, panic and disorientation can occur for building occupants. Ensuring the facility, egress ways, and mechanical rooms are clean and organized will enable people to exit properly even if elevators or escalators are not working. Additionally mechanical rooms often become "storage" areas for miscellaneous clutter, ensuring clean mechanical rooms will enable maintenance personnel to investigate essential service components without being impeded by excess clutter or debris.

Building Codes- New construction must adhere to adopted State or Federal code requirements, depending on the size/scale of construction renovation, those activities may also trigger the infrastructure or facility to come up to current code requirements. Many of the flood provisions required by building codes are contained in American Society of Civil Engineers (ASCE) 24, *Flood Resistant Design and Construction* (FEMA 2013). This code dictates if floodproofing is required, what height above BFE or design flood elevation (DFE) is required for essential equipment, and material requirements for equipment/anchors.

Image 74: *Anchoring Fuel Tanks.* Underground fuel tanks are being secured. Although underground, they could become buoyant in a flood (Tanks Direct 2015).

Image 75: *Rooftop Equipment.* Mechanical equipment is located on the roof. The higher elevation reduces its exposure to flooding (Fidelity Engineering Corporation 2013).

Relocate- There are times when it is more advisable to relocate essentials services or facilities housing the infrastructure completely out of the flood zone or an area that will become permanently inundated by sea level rise. This complete avoidance of water intrusion reduces exposure to threat. Relocation can be costly, but it can be incorporated into a long-term strategy to build resiliency by systematically moving infrastructure over an extended period, or when new facilities are planned, they are sited out of the threatened area.

Benefits: Sometimes it is not feasible to protect or relocate a whole facility, instead just the essential pieces of equipment can be addressed. This is a quick was to build in resiliency into the facility, and to ensure although there may be water damage to the facility itself, the building utilities will still perform. Major equipment pieces are one of the largest investments in facility, reducing their exposure, reduces the threat of damage and associated replacement costs.

Concerns: It is vital to do an assessment of all the essential services, and the physical location of all primary and ancillary equipment pieces. If the codependency of services is not understood then one essential service may be damaged if another was not a part of the adaptation strategy. Mechanical and equipment rooms are often tight spaces to begin with, raising equipment or floodproofing a room may be challenging due to physical space restrictions.

2.11 Retreat

The strategy of retreat promotes abandonment of land and structures in vulnerable areas, and resettlement of inhabitants (Dronkers et al. 1900). This strategy ensures no new development will take place within a designated retreat zone, and if development is allowed, those structures shall be built with the anticipation of eventual abandonment when required. Retreat allows the shoreline to erode or interface with the rising sea in naturalized processes, for example, wetlands are allowed to expand inland. Retreat as a large-scale adaptation strategy for developed areas is the most contentious, as related to economic, social, and political concerns, and may be better accomplished in systematic manageable scales (McGregor, Roberts, and Cousins, 2013).

2.11.1 Strategic Retreat

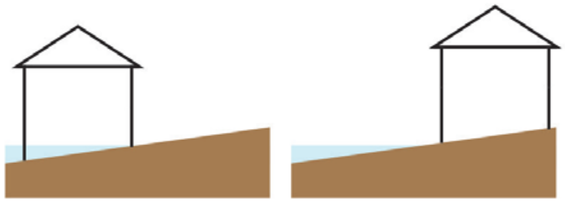


Figure 76: *Relocation* (NYC Department of Planning 2013a)

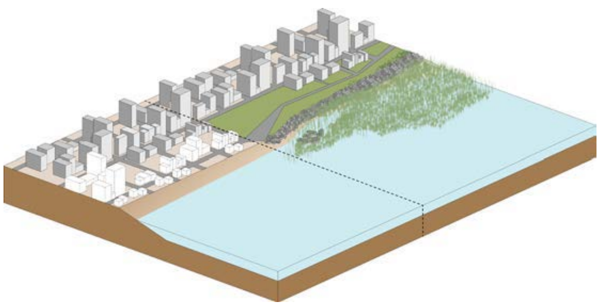


Figure 77: *Strategic Retreat* (NYC Department of Planning 2013a)

Strategic retreat is the process of removing infrastructure and development from areas vulnerable to sea level rise and flooding. Future development is not allowed in the retreat zone, and relocation of existing facilities and infrastructure is assessed based on operational requirements.

Figure 78: *Foster City, CA Coastal Retreat.* Aerial view of a strategic retreat, low lying developments on fill are abandoned (Wilson 2012).

Figure 79: *Surfer's Point Coastal Retreat.* In Ventura, CA, a managed retreat project created a green belt between the shoreline and upland infrastructure (RRM Design Group 2004).

Overview: Infrastructure and development is gradually demolished within a retreat zone. Those facility services are either abandoned or relocated into a new facility upland where exposure to sea level rise, storm surge, or flooding is reduced significantly or completely. A strong land use and installation community strategy needs to be created in order to lead decisions on how to fill the void in the retreat zone and how to infill development into upland areas. Planned retreat from the sea behind natural ecological defenses is one adaptation option. To maintain it, land could be set aside for colonization by coastal ecosystems, or buildings constructed on condition they are removed when sea level reaches a specified distance from the building (Abel et al. 2011).

Benefits: Risk and exposure is reduced significantly against coastal hazards, since development is completely removed from the exposure zone. In natural areas that are allowed to retreat, sandy beach ecosystems are able to adapt to sea level rise, by retreating landward slowly, allowing plants, and animals to migrate during that retreat in a natural manner (Berry, Fahey, and Meyers, 2013). This application is well suited for areas with low-density development or natural shorelines experiencing erosion, since the costs to relocate dense development could be incredibly costly. Although initially very disruptive, new open space is created along the shore for other uses such as wetland restoration, natural open space, parks, or open space for military training and operations. Upland structures out of the exposure zone may not have to incorporate other adaptation strategies for infrastructure or equipment specifically, if the threat of further coastal erosion moving inland is not a factor. Finally, once the initial cost of relocation is complete, facilities will not have to endure the repeated cost of damage or other adaptive strategies.

Concerns: Special consideration must first take place on where development will transition to, what will happen to existing development (will it be demolished), and what will remain in the vacant area. For military installations, where the government owns the facility and land in entirety, a strategic plan is more achievable, but within urban environments there is great concerns of the void left, and that it does not become an eyesore or cause other property values in the area to decline. Additionally who pays for the strategy to retreat, or relocate infrastructure. Even on military installations, there are varying military commands who occupy the space of a building. If a building is within the retreat zone, should the facility tenant pay for a new facility, or should in the case of the Navy, should NAVFAC secure funding.[10]

Coastal stakeholders' decisions are influenced strongly by rules, norms and incentives, in particular property rights, compensation, liabilities, and development controls (Abel et al. 2011). Military tenants although they do not own the facility, have great equipment and IT resources invested into a facility; they are not likely to want to relocate if there are no incentives in place for the disruption. Additionally unless the Navy and NAVFAC in particular, have strong arguments for sea level rise and actual projections, the argument for retreat is weakened by uncertainty.

Successful strategies to counter stakeholder objection to moving include, allocating authority and resources across levels of governance according to their effectiveness at each level – some devolution of authority and resources from higher levels to local governments may be a necessary condition for successful retreat (Abel et al. 2011). In context of the Navy, this means higher echelon commands such as Commander Navy Installation Command (CNIC), will have to first endorse a calculated plan of retreat on an installation, and then lower echelon commands such as NAVFAC Facilities Engineering Command (FEC) would have the authority to implement strategy locally.[11]

2.12 Literature Review Conclusion

The purpose of this literature review was to establish the role of climate change and specifically sea level rise in DOD and DON security and policy, to demonstrate the threat of sea level rise, storm surge, and coastal flooding on military installations, and to demonstrate current DOD and DON policy on mitigation and the clear gap of defined guidance in regards to adaptation. Finally, detailed examination

[10] Tenants on each base have varying funding streams. NAVFAC is funded by the DON to maintain facilities and infrastructure that are CNIC assets. Some tenants have more demanding facility requirements, such as Special Warfare Command or Bureau of Medicine. They receive funding from the DON separately, which is used to maintain or reinvest in facility upgrades.

[11] In the DON, echelon refers to the administrative chain of command, in which echelon I is the highest level of command, which is held by Chief of Naval Operations (CNO). NAVFAC Headquarters is a level II systems command, NAVFAC Atlantic and NAVFAC Pacific are level III commands, and nine Facilities Engineering Commands (FEC) are level IV and are spread throughout the world on a regional basis.

was completed on a spectrum of adaptation strategies for sea level rise through the lens of *Protect, Accommodate,* and *Retreat*. The chapters that follow provide a thorough analysis on how each of the adaptation strategies examined above directly support military physical and operational readiness, as well as provide a systematic risk assessment and adaptation selection process in which military coastal engineers can employ in order to mend the gap between sea level rise mitigation and adaptation policy.

3. METHODOLOGY

3.1 Introduction

This chapter discusses how research was conducted to answer the thesis questions, and how the thesis questions shall be answered by systematically creating a risk identification process for the United States Navy, an exploration of each adaptation strategy presented in the Literature Review was conducted in the context of cost, time, maintenance, environmental impacts, and built robustness parameters, and finally how a *Protect, Accommodate, or Retreat: Spectrum of Adaptation Strategies* matrix was developed.

3.2 Grounded Theory and Inductive Research

There is an abundance of qualitative data and information related to conducting a natural disaster risk analysis and on the spectrum of adaptation options available to counter sea level rise, storm surge, and coastal flooding, but there are no documents that concisely demonstrate how to logically apply that data into actionable policies in order to increase resiliency on military installations. Grounded theory methods consist of systematic yet flexible guidelines for exploring and analyzing qualitative data to construct theories grounded in the data themselves. Data form the foundation of the theory and the analysis of these data generate the concepts constructed (Atlcinsorr; P., Coffey, A., & Delamont, S. 2003 and Charmaz 2006).

In grounded theory, exploration is often informed by the researcher's professional experience, and leads the researcher to discover meaningful patterns and emerging theories based on a combination of professional background and data exploration. Theory is a guide, and without it, research is lost. There may not be explicit hypotheses, but this exploration is guided by the researcher's substantive knowledge, and tacit predictions are often made about where meaningful patterns will occur (Jebb and Woo, 2017).

The research conducted for this thesis was inductive in nature, by inducing progressively more related data, patterns of increasing resiliency on military installations were discovered, and compiled into a systematic risk analysis template. In addition, adaptation strategies were categorized according to criteria that is important to military leaders both operationally and physically.

Procedural steps followed to conduct grounded theory included:

- *Theoretical Sensitivity*-Selection of thesis topic, collection of data, and identification of characteristics. The process is based off of the academic familiarity with the thesis subject, but also based on personal experience and professional experience.
- *Constant Comparison*-Concepts were generated from thorough analysis of data and case examples.
- *Theoretical Sampling*- Sampling driven by the developing theory as the course of study continued and knowledge was refined. The goal was to develop a theory that was applicable to new situations that are similar to the settings in which the theory was generated.
- *Theoretical Saturation*- Research continued until no new concepts emerged, and the theory is supported by data (Oktay 2012).

3.3 Factors Critical to Military Resiliency

The first resiliency factor in this thesis is “physical resiliency” on military installations as related to environmental and infrastructure ability to withstand the effects of climate change and seal level rise. The second factor is “operational resiliency” as related to NAVFAC being able to meet its mission in supporting naval operations and readiness by being the Navy’s manager of shore infrastructure.[12] In

[12] Readiness measures the ability of a military unit, such as an Army division or a carrier battle group, to accomplish its assigned mission. Logistics, available spare parts, training, equipment, and morale all contribute to readiness (Spencer 2000).

order for the Navy to perform operationally, shoreline infrastructure needs to be in place to support the Navy's sea, air, special operations, and personnel requirements.

Resiliency both physical and operational, are dependent on the dynamics of understanding installation specific risk, choosing an appropriate adaptation strategy, timely implementation, and securing appropriate funding for the effort. To demonstrate how resiliency can be achieved, chapter 4 Results, concisely demonstrates the spectrum of adaptation strategies and how each strategy can increase resiliency. Each adaptation strategy is classified in how it creates resiliency in terms of cost, time, maintenance, environmental impacts, and built robustness inherent in the strategy. After review of all the adaptation strategies, coastal planners may choose to employ multiple strategies in order to obtain greater resiliency.

3.4 Methods of Investigation

In order to first fully understand the threat of climate change and specifically sea level rise, storm surge and coastal flooding, data was collected on current climate change science and trends. Science was collected from the most prominent and respected government agencies, including, but not limited to the IPCC and NOAA. All publicly available data and literature currently available for the Department of Defense and specifically the Navy on current climate change policy and guidance were reviewed, and strengths and weaknesses were identified. To fully understand the spectrum of adaptation options currently available, data in the form of scientific papers, case study analysis, and engineering performance guidelines were cross referenced for each strategy. It was critical to ensure that a multitude of data sources were collected for each adaptation strategy, in order to fairly assess the merits of each strategy without being influenced by one perspective. For example a structural engineer will have a very different perspective of the benefits of a hardened seawall, versus a marine biologist who studies habitat along natural or built shorelines. The key to inductive research is to gather varying data and opinions on the subject.

Finally, research was conducted by holding informal interviews with current NAVFAC personnel in order to ground truth theories that were generated during the development of the thesis. NAVFAC personnel were not given the authors theories or observations in advance, but instead discussions took place that allowed NAVFAC personnel to speak freely of their observations and opinions of current sea level rise policy and guidance in the field. Those practitioner observations and opinions were then compared to the authors theories in order to confirm or refine the grounded theory.

3.5 Risk Identification Development

Once climate change was validated as not only an operational, but also physical threat to military readiness, risk assessment policies for the Department of Navy were investigated. The author then cross-referenced DON and NAVFAC policies on risk assessment, and compared those to current risk assessment procedures that are used by the Department of Homeland Security, FEMA, and The World Bank. No one risk assessment procedure completely encompassed the needs for the military to view risk as related to operational and physical readiness. The DON's current system of risk assessment and emergency management focuses on understanding localized threats, and how emergency management teams respond, but does not look at how facilities and infrastructure lead to resiliency or vulnerability. This linkage of facilities and infrastructure to readiness must occur as a joint effort between subject matter experts who understand facilities (NAVFAC), and operational stakeholders (sea, air, and special operations commanders) who rely on those facilities in order to meet their mission. This linkage of facilities engineers with operational stakeholders, and their assessment of risk and adaptation selection as team is the foundation of the *Adaptation Evaluation Framework for Sea Level Rise, Storm Surge, and Coastal Flooding.*

3.6 Adaptation Strategy Exploration

Each of the adaptation strategies for sea level rise, storm surge, and coastal flooding were initially evaluated in the literature review, and classified as either a *protect, accommodate* or *retreat* strategy. Then those strategies were analyzed in the context of the military, and its resiliency framework that relies on operational and physical readiness ashore. The following factors are important to military shore readiness as related to facilities and infrastructure, and each adaptation strategy was evaluated by the following methodology, and an associated classification of High, Medium or Low was assigned to each category:

Cost: NAVFAC facilities engineers have competing requirements that require capital funding and operation and maintenance funds to be used in the most effective and widely impactful ways. With tightened military budgets, NAVFAC has a been receiving on average funding below its annual operations costs.

<u>Category Classification:</u>

-High- Projects that are estimated to have a cost above the Military Construction threshold of $2 million dollars.

-Medium-Projects that are estimated to have a cost between $500,000-$1,999,9999, since these projects are required to have a 1391[13] planning document generated, but still fall below the MILCON threshold. Due to their value they are typically monitored at the FEC level for implementation.

-Low-Projects below $500,000 that could be funded with locally controlled O&M funding at the Public Works level, and typically would not require a 1391.

[13] A 1391 is a military planning document that classifies data of a project related to scope, estimate, and justification of need. A 1391 is needed for all MILCON level projects, and the requirement for a 1391 slightly varies at each FEC for estimate thresholds below the MILCON threshold. Typically a 1391 is required for all projects over $500,0000.

Time: Both construction and service life were considered for time. Due to the level of engineering, design, permitting, and construction some projects may take several years to complete. In direct relation, those projects that take longer to implement, typically have a longer service life.

Category Classification:

-High-Project has detailed design, permitting and construction, which require a 18-24 month time frame at least. Service life is designed to last decades.

-Medium-Project construction may require some design and permiting, for a duration of 12-18 months. Service life is designed to last 5-15 years.

-Low-Project requires little design, and can be constructed in less than 12 months. Service life is anticipated for maximum of 5 years.

Maintenance: Infrastructure requires varying level of service in order to first maintain operation of the system, and second ensure longevity of the system. Additionally the level of skill, and cost associated with preventative maintenance varies. Finally, some adaptation strategies when employed require maintenance personnel to actively engage the infrastructure when a storm or flood event occurs; this introduces a higher level or maintenance for consideration.

Category Classification:

-High Maintenance and Reinvestment- Infrastructure requires a high level of service on an annual basis, and the costs associated with the reinvestment are close the replacement value of the system.

-Regular Maintenance and Reinvestment- Infrastructure has annual preventative maintenance schedule that has periodic smaller services throughout the year. Annual reinvestment is a small fraction of the overall replacement value.

-Low Maintenance and Reinvestment-Once the infrastructure is in place, there may be periodic inspection of the system, but does not require a detailed annual preventative maintenance schedule. Reinvestment is low, if any funds are required, since the system becomes self-sustaining.

Environmental Impacts: The Navy is required to be good stewards of the environment, and aims to protect environmentally sensitive areas. Shorelines shift naturally in response to sea level rise, some adaptation strategies allow this natural erosion to occur or attempt to prevent it, thus causing further restriction of natural based processes.

<u>Category Classification:</u>

-High-Infrastructure competes or destroys natural habitat.

-Medium-Infrastructure attempts to work in coordination with some elements of the natural environment. Some habitat is altered.

-Low-The natural environment is seen as an asset and the ecosystem based services are intimately involved with creating resiliency along the shoreline.

Built Robustness: Shorelines are dynamic environments that must counter the impacts of wave energy, rising sea levels, and occasional coastal storms. The more robust an adaption strategy is, the more it is able to withstand the impacts of flooding or storms, and remain in its original intended state.

<u>Category Classification:</u>

-High-Structure is made of materials that can withstand pounding waves or sea level rise. The structure is intended to create a firm delineation between the ocean/open water and upland infrastructure.

-Medium-Structure is made of materials that can withstand some wave action, and the shoreline may alter slightly after a significant flood or storm event.

-Low-Structure is not able to withstand substantial or continuous wave patterns. Shoreline erodes or is altered significantly after any storm or flood event.

3.7 Spectrum of Adaptation Strategies Matrix Development

In order to reach a decision on which adaptation strategy is most appropriate, a series of questions was established in order to guide the decision maker to consider:

-The context of the site, including the shoreline declination and water patterns.

-The budget, time and maintenance restraints, and how those factors influence military readiness.

-The environmental context, and localized policies that influence decisions.

-How is operational performance related to the physical environment.

Once those questions are answered, a spectrum of adaptation strategies presented in matrix form, was designed to be a planning and design tool that NAVFAC leadership and coastal facilities managers will use to refine their adaptation selection. The spectrum of adaptation strategies matrix allows decision makers to narrow down strategies that can first applied contextually, and then those which are appropriate contextually can be cross referenced and weighted according to their strengths and weakness related to military readiness. Military leaders and decisions makers have many competing requirements of their time, and in order to be effective the adaptation matrix must visually condense the pros and cons of each strategy concisely, and within terms that are relevant to operational and physical resiliency.

4. RESULTS

4.1 Introduction

In Chapter 2 of this thesis, 17 adaptation strategies were examined in the context of a *Protect*, *Accommodate*, or a *Retreat* approach, and in Chapter 3 five new factors were introduced in order to contrast and compare the merits of each strategy, and how it supports military physical and operational readiness. This chapter applies each of the factors, resulting in a thorough and pragmatic means of efficiently evaluating adaptation options available to military leadership and coastal facility managers. This chapter is divided into two sections; the first is the results of the five military resiliency factors applied to each of the 17 adaptation strategies. The second section is an *Adaptation Evaluation Framework*, which is broken down into three subcategories consisting of: (1) a risk assessment, (2) a systematic guide to choose the best adaptation strategy, and (3) methods of how to implement adaptation.

4.2 Military Resiliency Factors

4.2.1 Seawall

Cost *(High)*: Seawalls require extensive design and construction, and they are a high cost investment. Due to site and height variability, it is difficult to establish a per linear foot average. For comparison though, Seattle is replacing 3,700 feet of seawall at a construction cost of $410M, which calculates to be $110,810 per linear foot. Seattle's construction includes replacement of the existing seawall that support's much of the city's downtown infrastructure, including roads, freight routes, local and regional utilities, high-pressure gas mains, electrical and telecommunications wires and sewers (O'Connor 2016). In addition, the seawall will incorporate several innovative designs for marine habitat.

In New Orleans the Army Corp of Engineers is building a massive 26' high seawall that stretches around the city for 1.4 Miles. The main wall consists of 144-foot-long concrete piles extending 130 feet, below the mud line underwater, and is design to protect against a 500-year flood, projected to 2057 sea level rise scenarios. With a construction cost of $1.1B, that is a cost of $148,809 per linear foot (Irfan 2014). Both of the scenarios above are extreme public works projects that are extensive in scope and structure, smaller scaled projects such as the Virginia Beach Seawall which protects upland infrastructure for 3 miles along the Atlantic coastline, cost $53,427,825, or $3,373 per linear foot (S.B. Ballard 2016). Older seawall structures designed prior to sea level rise projections must be upgraded for sea level rise scenarios, or there is great concern of overtopping and upland flooding.

Time *(Long Lasting)*: Seawall construction requires full design, permitting, and construction. Due to the variety of scales, projects can take from a year to several years to construct. One of the main barriers to the implementation of a well-designed seawall is cost. The design of an effective seawall requires good quality, long-term environmental data such as wave heights and extreme sea levels. This is frequently unavailable in developing countries and can be costly to collect. Secondly, because seawalls are frequently exposed to high wave loadings, their design must be highly robust, requiring good design, significant quantities of raw materials and potentially complicated construction methods (Linham and Nicholls, 2016). With proper maintenance seawalls can last 75 or more years as planned in the Seattle seawall, and the seawall in Galveston, Texas is an example of a structure that is over 100 years old. Built originally in 1903, it still provides coastal flood and erosion protection (Dean and Dalrymple, 2002).

Maintenance *(Regular Maintenance and Reinvestment)*: Maintenance costs are another significant and ongoing expense when a hard defense is selected. These costs are ongoing for the life of the structure and are therefore likely to result in high levels of investment through a project's lifetime. Continued investment in maintenance is highly recommended to ensure defenses continue to provide design levels of protection (Linham et al., 2010).

Environmental Impact *(High)*: Environmentally seawalls can damage local marine ecology, but with design and construction efforts to mitigate environmental impacts, ecosystem services can be restored (Dyson et al. 2014). Concern is of coastal squeeze, and/or not enough light entering the water along with organic habitat surface for marine life to grow. Increased erosion can occur to adjacent natural shorelines because of wave reflections of the hardened seawall surface.

Built Robustness *(High)*: If maintained properly and designed anticipating sea level rise as well as storm surge possibilities, seawalls can increase human and built infrastructure resiliency. It is critical as the 2011 Tōhoku earthquake and tsunami in Japan demonstrated, to not overly rely in one form of resiliency adaptation. Humans should heed warnings during major storm events, and other critical upland infrastructure should have secondary adaptation options built in.

4.2.2 Revetments

Cost *(Low-Medium)*: Revetments are generally less expensive than bulkheads or seawalls. While costs vary significantly based on site-specific factors, construction costs generally range from $2,000 to $5,000 per linear foot (NYC Department of Planning 2013a).

Time *(Long- Lasting):* If not compromised from severe storm surge or water overtopping the structure, revetments have indefinite life spans.

Maintenance *(Low Maintenance and Reinvestment)*: Require very little maintenance unless major storm events cause rocks or geostructures to resettle in a structurally unsafe manner.

Environmental Impact *(Medium)*: Due to the nature of boulders or geostructures being present in a horizontal application, and water being allowed to flow through the structure, some marine life is able to persist.

Built Robustness *(Medium-High)*: Maintains a strong delineated shoreline, which protects from erosion due to waves and rising sea levels. As sea levels progresses though and overtops the structure, it will not protect from inland flooding. The sloped design and rough surface of most revetments have a lesser erosion and scour impact on adjacent sites as compared to vertical structures such as bulkheads and seawalls (NYC Department of Planning 2013a).

4.2.3 Bulkhead

Cost *(Medium)*: Costs vary widely depending on site-specific factors, but in general, a new sheet pile bulkhead can cost from $5,000 to $7,000 per linear foot. Raising bulkheads, where feasible, costs about $2,000 to $5,000 per linear foot, with generally higher costs for older structures. The excavation of older structures, drilling depth, labor costs, and site logistics for material delivery are all factors that can greatly increase the cost (NYC Department of Planning 2013a).

Time *(Long Lasting)*: With proper maintenance, structures, especially metal or concrete, can last for decades. Bulkhead construction requires full design, permitting, and construction. Due to the variety of scales, projects can take from a year to several years to construct, and require design and permitting stages that can take over a year for approval.

Maintenance *(Regular Maintenance and Reinvestment)*: As sea level rises additional structure or height may need to be added in order for the bulkhead to perform as intended. Periodic inspections are suggested, especially underwater to ensure material and structure are intact, this requires specialized divers.

Environmental Impact *(High)*: Environmentally bulkheads damage local marine ecology. Concern is related to coastal squeeze, and introduction of inorganic materials that do not support marine life. Increased erosion can occur to adjacent natural shorelines because of wave reflections of the hardened bulkhead surface.

Built Robustness (Low-Medium): They ensure structural stability for upland structures, ship mooring, and land that is prone to coastal erosion due to sea level rise and minimal wave action. In the event of a coastal storm, surge from the ocean may overtop bulkheads which can lead to structural failure when the soil behind the bulkhead becomes saturated and water levels recede creating pressure between the soil water and sea water (NYC Department of Planning 2013a). They are not built as robustly as a seawall, and do not have a freeboard height that allows for significant sea level rise or storm surge, they are intended to stop erosion from small waves.

4.2.4 Levees and Multipurpose Levees

Cost *(High)*: New levees vary based on the height of the levee, but typically range between $2,000 to $10,000 per linear foot. An armored levee can significantly increase costs to approximately $10,000 per linear foot. Additional underground pumping systems are typically also required (NYC Department of Planning 2013a Waterfronts).

Time *(Long Lasting)*: The Dutch have some of the most complex levee systems in the world which have been in place over 60 years, and have decades of continued use if maintained properly. Common reasons for failing include overtopping, erosion both along the foundation and internally. Due to the complexity of a levee, it can take several years to design, permit, and construct.

Maintenance *(High Maintenance and Reinvestment)*: Annual maintenance costs are approximately 2% of construction, and must completed in order to maintain structural integrity, as well as assurance of properly performing pumps. Multi-purpose levees auxiliary infrastructure must be inspected on an annual basis to ensure ground water intrusion has not affected utilities or structure.

Environmental Impact *(High)*: Shoreline is completely altered due to introduction of fill material, and the steep height of levees are not conducive to shoreline habitat unless specifically designed to create terraces for plant life.

Built Robustness *(High)*: If designed and maintained properly can provide excellent protection from sea level rise and coastal flooding. Although multi-purpose levees have great opportunities to harness the co-benefits of infrastructure being built within and upon the levee system, coastal planners must ensure they are not increasing the vulnerability of the installation by increasing the density of people and assets along the shore. As described in the literature review, protective coastal infrastructure in low-lying lands must not create a false sense of security or complacency.

4.2.5 Groins

Cost *(High)*: Besides initial costs, there are reoccurring costs for beach nourishment in downdrift areas. Multiple studies have been done on the reoccurring costs of beach nourishment for groins along the east coast. For example in North Carolina alone, the rate of renourishment cost has been an average of $5,900,055 per groin/per decade (Pietrafesa 2012). According to several ongoing Army Corp of Engineer projects, construction can range from $2 to over $90 Million dollars per system (USACE 2016a,b; United

States Fish & Wildlife 2016), or $1,500 - $3,000 per linear foot, depending on materials, and the site (NYC Department of Planning 2013a).

Time *(Long Lasting)*: Groins can last well over a 100 years as demonstrated in the Columbia River Gorge system built by the Army Corp of Engineers from 1885-1939. Continual upkeep is required though in order to restabilize structural materials, and renourish downdrift areas (USACE 2016a)

Maintenance *(Regular Maintenance and Reinvestment)*: Groins are recommended on the shores where sediments are available in a satisfactory quantity, either naturally or via artificial nourishment (Ostrowski et al. 2016). Beach nourishment will be an ongoing effort to enhance downdrift shorelines that are eroded. Frequency will be dependent on local ocean currents, and required after major storm events.

Environmental Impact *(High)*: The natural drift of sediment along a shoreline is interrupted, and although the structure lessens the amount of cross-shore erosion, the downdrift side of the groin becomes less stable and causes upland scouring adjacent to the groin.

Built Robustness *(Low-Medium)*: Groins and Jetties have limited application specifically to shoreline drift and erosion, and should be used in combination with other adaptation options such as beach nourishment. They are not effective against the rise of sea alone, but in certain applications protect valuable shorelines assets from erosion, and maintain shipping lanes within harbors.

4.2.6 Breakwaters and Floating Breakwaters

Cost *(Medium-High)*: Breakwater designs vary widely based on site-specific conditions and materials used, and costs are therefore difficult to generalize. Breakwaters can cost anywhere between $1,000 per linear foot to tens of thousands of dollars per linear foot (NYC Department of Planning 2013a).

Time *(Long Lasting)*: Engineering and permitting is required prior to construction, and can take over a year to obtain. With regular maintenance, Breakwaters can last 50-100 years. Sea level rise will diminish the effectiveness of the system over time.

Maintenance *(Regular Maintenance and Reinvestment)*: Regular inspection and associated maintenance is required in order to sustain the useful life of the breakwater. Floating breakwaters due to moving parts, and depending on materials (wood, rubber, metal drums), have more concern of damage during storm events.

Environmental Impact *(Medium)*: If maintenance of a natural shoreline is desired, breakwaters allow the natural migration of sediment and sand along the shoreline compared to a groin, but protect the shoreline from consistence pounding ocean waves.

Built Robustness *(Medium)*: Great care should be exercised when deciding the position of a solid breakwater. Solid vertical breakwaters do not absorb wave energy on them and reflect everything back, usually causing other parts of a harbor to experience "choppy-sea" conditions (Sciortino 2010). Provides increased resiliency for shoreline erosion and coastal storm surge, but does not prevent water intrusion from sea level rise.

4.2.7 Beach Nourishment

Cost *(Low)*: Relatively low initial expense compared to most forms of hardened infrastructure. An average beach nourishment project costs $20 to $50 per cubic yard (including transportation of sand). Costs vary based on the width and profile of the beach. Sand dune construction costs approximately $150,000/acre. Reinforced dune costs vary based on their core, and can range from approximately $300 linear feet for a simple reinforced dune to $10,000 per linear foot for a rock reinforced dune (NYC Department of Planning 2013a). Depending on the location of dredge sites, transportation to haul the sand can vary greatly.

Time ***(Short Lasting)*****:** Besides local and Army Corp of Engineers permitting requirements, beach nourishment projects are relatively straightforward and do not require extensive time to construct. Although initial construction can be measured in terms of months, the beach will have to be replenished with sand every 3-10 years.

Maintenance ***(High Maintenance and Reinvestment)*****:** An initial investment in planting native vegetation and grasses can extend the life as well as the environmental health of a project. It is critical at the inception of the project, that viable dredge sites are identified. Options include terrestrial (coastal sand deposits), backbarrier (sediment deposits in marsh, tidal creek, bay, estuary, lagoon), dredged material (from harbor/navigation/waterway projects), and offshore (ocean) sources. Sand sources vary greatly in quality (ebb and flood tidal delta sand classified as best, harbor dredging as worst); and cost (flood and ebb tidal least expensive, continental shelf most expensive) (NYC Department of Planning 2013a).

Environmental Impact ***(Medium)*****:** The environmental impacts are lesser than typical hardened infrastructure. Due to the nature of this form of adaptation it is considered to be more flexible, in the sense that it can be replenished at a later date, or hardened infrastructure can be added incrementally. It provides a buffer for upland infrastructure, but preserves a natural setting for recreation, water access, and shoreline habitats. Natural shorelines dissipate wave energy in a more natural flow, compared to hardened structures that may reverberate waves to another adjacent shoreline.

Built Robustness (Medium): In areas that have a natural shoreline, beach nourishment is an effective form of adaptation to diminish the impacts of waves, flooding and erosion. With sea level rise, replenishment is likely to become increasingly costly, because even smaller storms are likely to become more erosive (Hanak et al. 2011). Finally, although beach nourishment may not be the long-term solution, it can serve as an adaptive strategy until upland infrastructure can be relocated or retreat sufficiently.

4.2.8 Living Shoreline

Costs *(Low-Medium)*: Prices vary significantly based on pre-existing conditions, and if the living shoreline is completely natural or incorporated with another hardened adaptation strategy. Some of the common elements include: shoreline planting and wetland restoration (estimate costs $25-45/sq. ft.), geotextile grid shoreline stabilization (estimated costs $30/sq. ft.), and aquatic vegetation (estimated costs $2,000/sq. ft.) (NYC Department of Planning. 2013a). The value of economics and shoreline protection are not necessarily a linear relation. The non-monetary benefits of water purification, natural protection, and varied habitats are high though and can offset the construction costs, especially in areas that are designated as wetlands or environmentally sensitive to begin with (Barbier et al. 2008).

Time *(Long Lasting)*: Extensive permits can take 4 months or longer**,** and should be obtained in advance in order to accommodate the proper planting season. Due to the varying plants and shrubs to be planted, the construction can span several planting seasons. For grasses and herbaceous perennials, the best time to start construction is in the spring since plants are available from nurseries at the start of the peak summer growing season. Trees and shrubs are best suited for a fall planting season **(**Chesapeake Bay Foundation 2007). Once the shoreline has taken root, it can last indefinitely with minimal maintenance.

Maintenance *(Low Maintenance and Reinvestment)*: Once the shoreline plants have taken root, and begin to grow, there is minimal maintenance required to preserve the shoreline. Large debris, such as logs, algae mats, or trash, should be periodically cleared from the site to protect wetland plants from smothering (Chesapeake Bay Foundation 2007). As sea level rises though, living shoreline installations may need to be adapted to accommodate rising water levels, and additional shoreline elements such as rock and sediment may need to be placed further inland.

Environmental Impact *(Low)*: Living shorelines are an excellent option for marsh, bay, or wetland areas experiencing tidal erosion and damage from storm surge. By using native plants, rocks and sediment to stabilize the shoreline, the ecosystem services are restored that keep the physical structure of the shoreline stable, while also promoted species diversity. If properly design with upland structures, hybrid living shorelines can allow storm flooding by creating an area to hold excess water, while ensuring the shoreline remains stable as water recedes.

Built Robustness *(High)*: Recent studies after category one hurricanes show that marshes with and without sills are more durable and may protect shorelines from erosion better than traditional bulkheads (Gittman et al. 2014). In addition, natural marshes and living shoreline approaches to shoreline management may come with a substantial carbon benefit, versus hardened structures (Davis et al. 2015). Finally, sea level rise can eventually inundate upland structures, if the shoreline is not allowed to retreat or if additional sediment, rocks, and plantings are not placed to raise the overall elevation of the shore.

4.2.9 Constructed Wetlands

Cost *(Medium)*: On average, a new constructed wetland costs $700,000 to $1,000,000 per acre. Restoring degraded wetlands and shoreline planting is generally less expensive (NYC Department of Planning 2013a). When considering constructing wetlands for sea level rise and coastal flooding perspectives, the initial monetary cost should not only be considered in the evaluation, the other co-benefits of carbon mitigation, stormwater treatment, and habitat improvements are additional values to be considered.

Time *(Long Lasting)*: Extensive permits can take months to a year to attain**,** and should be obtained in advance in order to accommodate the proper planting season. Due to the varying plants and shrubs to be planted, the construction can span several planting seasons. Vegetation selection needs to accommodate the hydraulic operations of the wetland system and still support habitat objectives. In general, use a diversity of native, locally obtained species. You should obtain seeds from a local seed bank or seedlings from a local nursery, whenever possible. Native plants from existing wetlands may be harvested provided that removal of the plants does not result in damage to the existing wetland or violate any applicable Local, State, or Federal regulations (EPA 2000a).

Maintenance *(Low-Medium Maintenance and Reinvestment)*: Part of benefit of a wetland is that there is minimal maintenance after plants have rooted. For the long-term health, wetlands should be monitored periodically though, to ensure their maximum health. Examples of maintenance activities that you should conduct during these inspections include checking weir settings and the inlet and outlet structures, cleaning off surfaces where solids and floatable substances have accumulated to the extent that they may block flows, removing nuisance species and maintaining the appearance and general status of the vegetation and wildlife populations, and removing sediment accumulations in forebays (EPA 2000a).

Environmental Impact *(Low)*: Wetlands provide co-benefits of natural habitat, stormwater runoff treatment, shoreline stabilization, flood protection, and if allowed to migrate inland can reduce the threats of sea level rise.

Built Robustness *(High)*: Coastal vegetation can clearly play a role in reducing storm surge and coastal inundation in gently sloping shelves. Effectiveness of the vegetation in dissipating storm surge and inundation depends on the intensity and forward speed of the storm as well as the density, height, and width of the vegetation canopy (Sheng et al. 2012). They are ideal for natural shorelines with low wave energy, but are not suitable for built up shorelines.

4. 3 Accommodate

4.3.1 Dry Floodproofing

Cost *(Medium)*: For new construction, prices will vary greatly on the size of the facility, the foundation thickness, the type of structure used, and the number of penetrations that must be sealed. In general, dry floodproofing is usually more expensive than wet floodproofing for new construction. An integral floodproof gate on a door will add several thousand dollars to each penetration. Cost estimates for retrofitting an existing building with dry floodproofing range from approximately $1.5 million for a low-rise retail or industrial building to $6 million for a commercial high-rise (NYC Department of Planning 2013a). There can be high-unintended costs if the dry floodproofing has any form of failure, and interior assets are damaged. If there is not space or funding for other protective measures such as seawalls or revetments, dry floodproofing is a viable alternative for occasional storm surge or flooding.

Time *(Medium Lasting)*: For new construction, dry floodproofing will be coordinated into the existing schedule, since most of the materials and structural capabilities are just an enhancement of material and structure that would be built in typical construction. Floodgates and deployable gates add minimal time to the overall duration of a project. Retrofitting a structure requires design, permitting, and construction, and when added together will require at least 12-18 months. For both applications, once completed the system is integral to the facility and with maintenance should last the life of the facility.

Maintenance *(Regular Maintenance and Reinvestment)*: Periodic maintenance is required to examine and repair seals, as well as the inventory list of all support gates or barriers should be reviewed (FEMA

2007). Automatic floodgates should be tested periodically to ensure proper functioning. Dry floodproofing is not recommended for areas which experience prolonged flood events because most sealing systems will begin to leak after prolonged water exposure (NYC Department of Planning 2013a).

Environmental Impact *(Medium)*: Building materials that are exposed to prolonged periods of water may deteriorate, and need replacement. Special care must be used when cleaning up after a flood event, since standing water and wet building materials promote mold growth and are hazardous to human health.

Built Robustness *(High)*: In general, permanent floodproofing measures are most effective when used in areas that are subject to frequent flooding, relatively high flood depths, or where insufficient flood warning time is available to implement contingent floodproofing measures (FEMA 1986). Dry floodproofing creates additional resiliency for a facility, especially if the system is maintained properly, and if it is used with other protective measures along the shore. From a facility perspective, floodproofing allows the use of floors at grade or below, and ensures contents within the facility are not damaged due to storm surge or flooding. If deployable flood barriers are utilized, this requires humans to physically place the structure in anticipation of a flood. The barrier and tools must be kept in a close location, and if personnel do not know how to install the flood barrier properly the entire floodproofing system can fail (FEMA 1986). That is why floodproofing in a facility must be linked with actual training of personnel, and having an emergency plan on how to exit the facility encase of an impending flood. Flood proofing is not intended to counter the effects of sea level rise and permanent water intrusion.

4.3.2 Wet Floodproofing

Costs *(Low-Medium)*: Cost estimates for wet floodproofing of existing buildings range from approximately $100,000 for a detached one to two family house to $1.5 million for a high-rise residential or commercial building. Wet floodproofing is generally less expensive than dry flood-proofing, and varies based on number of vents added, surface area to be painted with sealants, and if the first floor structure must be raised (FEMA 2007, NYC Department of Planning 2013a). Extensive cleaning is required after a flood event, and damaged materials will need to be replaced. The space may have residue of chemicals, sewage, or hazardous materials carried in by the flood.

Time *(Medium Lasting)*: For new construction, wet floodproofing will be coordinated into the existing schedule, since the addition of vents or penetrations can be coordinated with the installation of the foundation. Retrofitting a structure requires consultation with a design engineer, and based on the complexity can require design, permits, and construction. For both applications, once completed the system is integral to the facility and with maintenance should last the life of the facility.

Maintenance *(Regular Maintenance and Reinvestment)*: Annual maintenance is limited, but is required to monitor floodwater vents and openings, to ensure impervious sealants are still intact, and to ensure sump pumps are operational.

Environmental Impact *(Medium)*: Building materials that are exposed to prolonged periods of water may deteriorate, and need replacement. Special care must be used when cleaning up after a flood event, since standing water and wet building materials promote mold growth and can be a hazard to human health.

Built Robustness *(Medium)*: Wet floodproofing is a viable option for lightweight structures to resist the structural damages of large hydrostatic pressure during a flood or storm surge. It does not protect against large waves, fast moving currents, or sea level rise inundation. In the right context, it pairs well with warehousing, entry circulation, or parking structure type facilities, which will endure minimal interior damage from floodwater. Once the flood begins to recede, it is important to not pump out water too soon, since this can cause a pressure imbalance with heavily saturated soil remaining on the outside.

4.3.3 Elevate

Cost *(Medium)*: For mound projects, the primary cost is hauling in fill, and site work to grade and install drainage to the site, this can range from the tens of thousands to several hundred thousand dollars. This cost will fluctuate greatly due to the size of the site, and if retaining walls are required, but in general, it is less expensive than installing other hardened structures such as seawall. New construction that utilizes piles vary based on the number of piles and the ability to get a pile driver into a site. Since there is no foundation the expense of pile driving is offset. FEMA has produced general guidelines for the estimated cost of elevating an existing structure that ranges from 32$ per square foot for a wood frame on concrete or block foundation, to 45$ per square foot for building that is slab-on-grade (FEMA 2007). In general, to elevate an entire 1-2 smaller[14] detached building will cost approximately $60,000 to $200,000, depending on site-specific factors (NYC Department of Planning 2013a).

Time *(Long Lasting)*: New construction efforts required design, permitting, and construction which takes about 18-36 months, and is similar to the construction schedule of typical construction, although there will be additional emphasis on site or structural work to drive piles. Raising an existing structure requires engineering, permits, and actual construction, this process takes 9 months to over a year.

Maintenance (Low Maintenance and Reinvestment): Once constructed or lifted, there is no additional maintenance besides typical maintenance of a facility. Now if structures on piers have wet floodproofed walls around the perimeter, or dryproofing around elevator/stairwell shafts, those should be inspected annually for water sealant quality, and properly working vents.

[14] FEMA referenced the size of a house, so typically between 1000-3000 sqft. Depending on the value of the facility itself, it may be more cost effective to demolish it and rebuild.

Environmental Impact *(Medium)*: Based on site conditions significant regrading may be required to elevate the site, special attention must be focused on new drainage and flood patterns are created for adjacent sites. Special care must be used when cleaning up after a flood event, since standing water and wet building materials promote mold growth and can be a hazard to human health.

Built Robustness *(High)*: Elevating a structure outside the high water mark of design flood levels increases the resiliency of the facility, and ensure the safety human life and assets. Designs that project for anticipated sea level rise, and mean high tide levels will add decades to the lifespan of a facility. Large coastal waves and flooding can exert strong hydrodynamic forces on any building element that is exposed to the waves or flow of water. Therefore, foundations that offer minimal resistance to waves and floodwaters passing beneath elevated buildings (e.g., pile and column foundations) are required in Coastal High Hazard Areas[15] as defined by FEMA. Stairs, ramps, elevator shafts, or even lateral bracing can impede powerful waves during a storm, and can shear and damage the structure attached above if not designed properly (FEMA 2008). In the case of elevating a residential home, insurance premiums typically are lowered.

4.3.4 Floodwalls

Cost *(Medium)*: Floodwalls can range in cost due to the materials used, the height, and width of the system. On average, systems cost between around $92 per linear foot for a 2' tall wall, $140 per linear foot for a 4' tall wall, and $195 per linear foot for a 6' tall wall (FEMA 2007). As the size of the site increases, materials are upgraded, or with additional jogs and bends in the system to accommodate site

[15] A Coastal High Hazard Area has special flood hazard extending from offshore to the inland limit of a primary frontal dune along an open coast and any other area subject to high velocity wave action from storms or seismic sources. The coastal high hazard area is identified as Zone V on Flood Insurance Rate Maps (FIRMs). Special floodplain management requirements apply in V Zones including the requirement that all buildings be elevated on piles or columns (FEMA 2016b).

Area V zones are along coasts subject to inundation by the 1-percent-annual-chance flood event with additional hazards associated with storm-induced waves. Because detailed hydraulic analyses have not been performed, no BFEs or flood depths are shown. Mandatory flood insurance purchase requirements and floodplain management standards apply (FEMA 2016c).

parameters, the price can go up significantly. Removable systems require storage on site, and a stand-alone storage facility can add to the project cost if required.

Time *(Medium-Long Lasting)*: As with any construction effort, design, permitting, and construction takes about 18-36 months. Projects that are maintained become a permanent addition to the site, and can last decades.

Maintenance *(Regular Maintenance and Reinvestment)*: Permanent structures require very little maintenance, but as with any structure, repairs to the foundation, settling cracks in the structure, or erosion/scour from previous floods along the foundation must be addressed, or those problems can become weaknesses during an actual flood event (FEMA 2007). Removable structures on the other hand should be inspected for structural integrity, especially after they have been deployed or shifted within storage facilities. Inventory lists should be monitored and training should be done periodically so maintenance staff are familiar with how to employ the system. Floodwalls must be designed to avoid trapping stormwater behind the wall, so pumps and stormwater runoff must be coordinated with the design (NYC Department of Planning 2013a).

Environmental Impact *(Medium)*: Although robust in nature, require a much smaller footprint than a levee or berm, and can be coordinated with landscape design.

Built Robustness *(Medium)*: Serves as a viable option to counter periodic flooding or storm surge events. For military and secure facilities, the system can be incorporated into the physical security of the building creating a co-benefit. Special attention should be paid to observation and maintenance of the system, to ensure no small weakness become major failures in a flood or storm surge event. This approach can be incorporated into one building or a complex of buildings. The system is not constructed for the long-term threat of sea level rise similar to a levee; the permanent hydrostatic pressure of water would reduce the structural stability of the foundation. Seepage beneath the floodwall and the natural capillarity of the soil layer may result in a water level inside the floodwall that is equal to or above grade. This condition is worsened by increased depth of flooding outside the floodwall and the increased flooding duration. Unless this condition is relieved, the effectiveness of the floodwall may be compromised (FEMA 2013).

4.3.5 Floating Structures

Cost *(High)*: In a commercial setting the technology has limited precedence, but the base cost addition to a small structure the size of a home adds approximately $60 per square foot according to IMF, a Canadian manufacturer of floating platforms, and any additional costs for access ramps and utility connections must be considered (NYC Department of Planning 2013a). Since 2004 the U.S. Navy has been conducting ongoing tests on a double-deck floating pier, now with the technology proven, they estimates that a 1300 feet long double-deck floating pier will cost $45 Million dollars (NAVFAC 2013).

Time *(Long Lasting)*: Design, permitting, and construction will vary based on the complexity of the structure and whether the structure is replacing an existing asset. Construction can take place offsite though in a facility or dry dock and then floated to the site, this saves actual construction time on site.

Maintenance *(Regular Maintenance and Reinvestment)*: Scheduled inspection of the structural integrity should be done periodically and preventative maintenance should be done at stress points, such as the connection from structure to shore. Additionally since utilities are run to the system, special care should be considered for containment of any fuels, wastewater, or sanitary sewer.

Environmental Impact *(Medium)*: Although there will be some environmental impacts due to its proximity over the water and lack of sunlight accessing the water for marine life, completely floating structures void of piers minimize the impacts of infrastructure along the sea floor.

Built Robustness *(High)*: Floating structures and specifically piers, provide incredible resiliency against sea level rise and fluctuating tides. They increases operational readiness by allowing more efficient ship to shore movement of supplies and equipment. The also present a unique advantage for locations with deep water or poor soils, since piles do not necessarily have to be driven to secure the structure. Additionally the structure is more resilient, because it is flexible during earthquake activity, cyclonic storms, or sea-level change (NAVFAC 2013).

4.3.6 Planning Regulations and Tools

Cost *(Low)*: Although creating policy, and gathering knowledge in the form of studies and reports is an expense of human capital, the actual cost of applying regulation is negligible compared to implementing outdated regulations that do not consider sea level rise, storm surge, or updated flooding scenarios. Now the actual cost of design and construction may increase, but the act of enforcing regulations does not. In a larger context, if regulations do not allow specific parcels to be developed with built infrastructure, then the value of that land may decrease.

Time *(Long Lasting)*: Creating a vision, updating regulations, and creating a climate action plan can take several months to over a year based on involvement and feedback from stakeholders. Monitoring the coastal environment and knowledge gathering should be a continual effort. Creating an adaptation priority list with projects should be done on an annual basis, and should be coordinated with securing annual funding.[16]

Maintenance *(Regular Maintenance and Reinvestment)*: Regulations should be reviewed periodically to analyze their effectiveness. Those regulations that have been found to have contradicting or adverse effects on the installations environment, operations, or economic wellbeing, may need to be reevaluated. Of note, just because a regulation creates challenge in the design or construction process, does not mean it is negative to the wellbeing of the installation.

Environmental Impact *(Low)*: Planning regulations and zoning can be used to preserve existing ecosystems along the shoreline, and to ensure that new infrastructure is built with low impact development methods[17]. Holistically on an installation level, sea level rise adaptation plans can balance areas that must use hardened shoreline infrastructure, by setting aside natural areas that will be preserved or returned to their intended ecosystem service.

Built Robustness *(High)*: Planning regulations and tools are an excellent way to increase resiliency, because the intended initial goal is to reduce exposure to risk by not placing buildings or infrastructure in harms way. Regulatory tools can also be used in accordance with a land use plan to promote the long-term reduction of a community's exposure to coastal hazards by reducing the permitted scale or density of new development. Limitations on redevelopment can also be enforced, such as rebuilding restrictions set forth in building codes or zoning that enforce limitations on the ability to rebuild once a structure has been substantially damaged (NYC Department of Planning 2013a). For existing facilities and

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[16] The U.S. Navy's annual facility and utility budget is broken down into sustainment, restoration, and modernization funds. Projects are assigned to one of those funding classifications, and the funding for a project must be awarded with a contract in the same year as the funds were received. The U.S. Navy's fiscal year is from Oct 1st –Sept 30th each year. Projects that are classified as military construction (MILCON) have funds that are available for award and must be obligated in a 5-year period.

[17] Low impact development uses natural practices that use or mimic natural processes that result in the infiltration, evapotranspiration or use of stormwater in order to protect water quality and associated aquatic habitat (EPA 2017).

infrastructure, resiliency will increase by having a strong grasp of the vulnerabilities, and then a vision on how to adapt in a systemic way, with clear direction and tangible actions.

4.3.7 Essential Systems and Equipment Assessment and Action

Cost *(Low-Medium)*: The cost will vary depending on the equipment piece, and the adaptation strategy. Anchoring, sealing building joints, installing back-flow protectors, and/or general housekeeping are straightforward costs that are minimal- to being tens of thousands of dollars. Dry floodproofing, building an enclosure or relocation are higher expenses that range up to $1.5 million for an entire low-rise retail or industrial building (NYC Department of Planning 2013a). A smart strategy is to cross-reference the prioritized assessment of pieces of equipment that need to be adapted, and then review the service life for the pieces of equipment. It may be a better option to adapt when the essential equipment was scheduled to be replaced anyway. If there is still a long service life, the financial investment in adaptation often outweighs the operational cost of losing operational readiness, capability, or human safety/health.

Time *(Long Lasting)*: Based on adaptation strategy, adaptation strategies can take only weeks to months for anchoring, sealing building joints, installing back-flow protectors, and/or general housekeeping, to over a year for construction projects to install dry floodproofing enclosures or relocation of equipment.

Maintenance *(Regular Maintenance and Reinvestment)*: Periodic maintenance and monitoring for adaptation strategies should be incorporated into the existing maintenance schedule for each pieces of equipment. Additionally there should be a location list and inventory of all support gates or barriers required for dry floodproofing (FEMA 2007).

Environmental Impact *(Low)*: Adaptation takes place on pre-existing equipment, so there is no new land required for the upgrades unless moved. Pieces of equipment that are relocated can be moved to sites that do not have environmental conflicts. Sealing equipment and ensuring it is secure, is better for the environment because it ensure no hazardous fluids will escape in the event of a flood.

Built Robustness *(High)*: Complete essential service and equipment adaptation will not be a quick effort for a large installation with numerous facilities and/or pieces of infrastructure; instead, adaptation should be viewed as an ongoing effort, which must be systematically incorporated into each year's sustainment, restoration, and modernization budget, and within each year's new construction budget. With a systematic approach of adapting essential services and equipment, exposure to risk is decreased significantly and resiliency is increased. In the event of a storm surge or flood, disorder can occur, by ensuring that power, potable water, communication systems, and basic life-safety systems are in working order, coordinated recovery efforts can begin much quicker.

4.4 Retreat

4.4.1 Strategic Retreat

Cost *(High)*: Demolition and relocation of a facility or complex of facilities is the most expensive option in the short term. In making a determination on this strategy, those costs must be balanced with the projected incremental costs of employing other adaptation strategies, as well as maintenance and repair costs associated with sea level rise, storm surge or flooding. The Navy must balance the mission and operational cost savings[18] that are incurred by working in areas that are prone to sustained coastal threats.

Time *(Long Lasting)*: Relocation of a facilities or infrastructure is a multi-year to multi-decade effort, which is intricately coordinated with the installation's comprehensive and operational strategic plan.

[18] Savings in the context of operations is associated with the savings of time or ease of doing operations closer to the shoreline.

Maintenance ***(Low Maintenance and Reinvestment)*****:** Once out of the inundation zone, maintenance on facilities follow the typical preventative maintenance schedule designed for the facility and equipment.

Environmental Impact ***(Low)*****:** This strategy greatly increases the resiliency of coastal ecosystems in their natural roles as beaches, dunes, wetlands, salt marshes and habitats for plants and animals, while also increasing the resiliency of the shore against further erosion (Barbier et al. 2008, Caldwell, and Holt Segall, 2007).

Built Robustness ***(High)*****:** Infrastructure and facilities moved upland have great increased resiliency, since exposure to coastal threats has been significantly reduced. This strategy as a whole is the most invasive to the community, and requires an incredibly coordinated vision, land use plan, comprehensive plan, operational plan for the installation, large financial investment, and strong buy in and support from leadership and stakeholders at all levels. If those elements of planning are assertively coordinated and fostered, then the approach of strategic retreat can also create community resiliency in the form of empowering people and organizations.

4.5 Adaptation Evaluation Framework

The *Adaptation Evaluation Framework for Sea Level Rise, Storm Surge, and Coastal Flooding* is a step-by-step guide that encourages naval installation coastal managers to analyze risk not only from a physical perspective, which is relevant to infrastructure and facilities, but also through the unique lens of operational factors inherent to the U.S. Navy. Resiliency is viewed not only as something to obtain physically through built form, but also through emergency management teams, emergency operations plans, and by empowering installation personnel to be a part of increasing overall resiliency. The framework below is intended to be a step-by-step guide. Although each step should be completed, installation coastal managers must use their discretion in determining if each task and deliverable applies to their select installation.

TABLE 4: ADAPTATION EVALUATION FRAMEWORK

For Sea Level Rise, Storm Surge, and Coastal Flooding

(Caponigro 2017)

RISK IDENTIFICATION	**STEP 1: Acknowledge and Understand Risk** *Each installation shall understand the specific risks associated with sea level rise, storm surge, and flooding to their unique location, and will pledge a commitment for increased resiliency.*
RISK IDENTIFICATION	**STEP 2: Gather Risk Assessment and Resiliency Team** *Installation Stakeholders are identified for their unique role in installation operations and management, and feel empowered to increase resiliency within their functional role.*
RISK IDENTIFICATION	**STEP 3: Data Collection** *Data shall be collected in the forms of maps, facility inventories, equipment lists, operating procedures, projected sea level rise, and historic storm and/or flooding events.*
RISK IDENTIFICATION	**STEP 4: Exposure and Vulnerability Analysis** *Collected data shall be reviewed in coordination and analyzed for exposure and vulnerability. Physical infrastructure and environmental conditions shall be reviewed against operational and personnel requirements.*
ADAPTATION SELECTION	**STEP 5: Managing, Balancing, or Reduction of Risk** *Risks shall be evaluated against personnel safety, operational requirements, and costs to determine the level of risk that is acceptable to maintain.*
ADAPTATION SELECTION	**STEP 6: Adaptation Selection** *Adaptation strategies shall be explored and chosen.*
IMPLEMENTATION	**STEP 7: Implementation** *Timelines, funding, and responsible agents for strategies are identified.*
IMPLEMENTATION	**STEP 8: Monitor and Review** *Adaptation strategies are monitored for their success in creating resiliency and reducing risk, and altered if not performing well. New risks are identified if applicable.*

4.6 Risk Identification: Step 1-4

For each installation NAVFAC staff should conduct a risk assessment specifically related to sea level rise, storm surge, and flooding risks. The approach below addresses long-term threats such as sea level rise, but also aims to identify risk and build resiliency for rapid onset risks such as storm surge and flooding. There are 4 steps for the risk assessment, and each step is broken down into overall goals, tasks, and deliverables. Based on the site conditions, existing resources, and buy-in from all stakeholders, each step's tasks and deliverables may or may not apply. The importance of the systematic approach is to look at risk in regards to the individual hazards, exposure, and vulnerabilities unique to each installation, and how those can be reduced not only by physical measures, but also by policies and procedures that are implemented by command leadership.

The Federal Emergency Management Agency (FEMA) has defined emergency preparedness as preimpact actions that provide the human and material resources needed to support active responses at the time of hazard impact (FEMA 2006). It is the process of an agency to conduct a hazard vulnerability assessment, and in doing so thinking through all the possible disaster related threats that could cause physical and economic harm. Once risks and associated threats are determined, actions can be taken to mitigate and adapt to the threat and create resiliency in the built environment. In addition, communication plans and emergency operation plans can be established well in advance. The benefit of having these tasks done in advance is that it allows the impacted groups time to logically think through all the steps of preparedness, without the chaos of an impending disaster, plus allows time to actually adapt in a systematic manner.

4.6.1 STEP 1: Acknowledge and Understand Risk

Goal: It is important for NAVFAC and specifically Public Works Departments assigned to each installation to first acknowledge that sea level rise, storm surge and flooding are a threat to coastal installations, and then understand by acting earlier, decisions and adaptation measures can be made to increase resiliency steadily against the risk. NAVFAC staff must first understand the basics of their risks in order to properly engage stakeholders, and convey risk. Although further detailed analysis of exposure and vulnerability are evaluated later in the process of risk assessment, a basic understanding and commitment to resiliency promotes education and buy-in from other stakeholders in the initial stages of risk assessment.

Tasks:

- Review past trends of sea level rise, storm surge, and/or coastal flood events. What damage has occurred in the past, think in human, operational, and financial terms.
- Understand the basic projections of sea level rise within the region, and understand the basic occurrence of storm surge or flood events.
- Assign key NAVFAC planning personnel responsibility for risk assessment implementation. Having one person or a small group charged with the overall implementation of risk assessment creates accountability.

Deliverables	
Each installation shall understand the specific risks associated with sea level rise, storm surge, and flooding to their unique location, and will pledge a commitment for increased resiliency.	Sea Level Rise, Storm Surge, and Flood Data
	Sea Level Projection Rise Maps
	Regional Context Maps with Major Waterways
	Assign a Designated Risk Assessment Leader and Team

4.6.2 STEP 2: Gather Risk Assessment and Resiliency Team

Goal: Installation stakeholders which include installation leadership, NAVFAC leadership, and operational command leadership must understand the risks of climate change and related sea level rise, storm surge, and coastal flooding, and how those risks impact their operational requirements. Stakeholders are committed to building installation resiliency that not only considers physical infrastructure, equipment, and the environment, but also values operational and personnel readiness. Although the focus of this paper is on increasing resiliency to installation infrastructure and the environment, all stakeholders must be involved with risk assessment and resiliency planning to ensure the full spectrum of actions are considered, and total resiliency across installation functions is increased.

Tasks:

- Identify and sensitize key stakeholders to the basic concepts of disaster risk management and climate change adaptation through workshops and information sessions. Participants of these meetings would ideally be composed of a broad range of stakeholders, including staff engaged in urban planning, environmental services, disaster preparedness and response, water and sanitation services, security, fire, and health services (Dickson et al. 2012). Within a military installation, operational commanders responsible for major naval assets such as ships, aircraft, special operations, and personnel are also critical to understanding and countering risk.

Deliverables	
Installation Stakeholders are identified for their unique role in installation operations and management, and feel empowered to increase resiliency within their functional role.	Role and Contact List of Stakeholders
	Hold Initial Risk Awareness and Planning Workshop
	Create Planning and Coordination Schedule
	Assign Action Items
	Create Protocol for Knowledge Sharing

4.6.3 STEP 3: Data Collection

Goal: Risk is present for both physical factors such as facility infrastructure and environmental cohesion along the shore, but also in operational factors of the Navy such as the ship, aircraft, special operations equipment, and personnel that support those operations. The function of a Naval installation is to ensure that operations are supported, and Naval readiness is achieved in combination of equipment and manning, that is why it is critical the risk must not be viewed through separate lenses, but as linked concerns. In order to understand the linkage of physical and operational risk, data must be collected to demonstrate support relationships. Additionally some installations are large in scale, it must be determined if the entire installation is to be assessed or areas within a defined area near the coastline.

Tasks:

Physical Factors

- Generate maps that show sea level rise, storm surge, and flooding scenarios specific to the installation. Sea level rise has varying projections and time horizons, so a series of maps may need to be produced.
- Asset Management Lists for naval facilitates and infrastructure should be reviewed, and updated. Current facility condition, maintenance logs, and future upgrades should be listed. The structure and façade materials should be listed. The first floor height and if a crawlspace/basement is present should be accounted for. Critical equipment and location within the facility must be accounted for.
- Utility system plans must be developed to demonstrate locations on the installation, the overall height of where the utility system or equipment rests, and what other utility systems does the system serve or depend on.

- Collect financial information on each pieces of infrastructure or equipment. What is the replacement cost, what ongoing maintenance costs area associated, and what streams of funding are available and allowed to make improvements.
- Collect information on environmental considerations, are there protected lands within the installation, are there archaeologic or culturally sensitive areas.
- Define all current building codes, environmental policy, or federal policy related to climate change, sea level rise, and/or disaster preparation/management.

Operational Factors

- Define the key mission of the installation (sea, air, special operations, training, etc.).
- Identify all the tenant commands on the installation, what facilities/infrastructure are the assigned to, do they pay for utilities or facility space.
- What support infrastructure and facilities do they rely upon for their operations. For example, although an airplane squadron may be assigned to a specific hangar, squadron operations heavily rely on runways, apron, taxiways, runway lighting, fuel farms, weapon storage, and tower operations.
- Personnel are essential to Naval operations, do most sailors live on base, are there family housing units on base. What support elements such as medical centers, child development centers, commissary or exchange services are on the installation.
- Operational schedules must be understood. Depending on installation operations, are there requirements for a certain number of tenant commands to be deployed or at homeport at any time throughout the year. For example if an installation has 3 aircraft carriers always assigned, is there a requirement that 2 are always deployed, and one in homeport. Operational schedules dictate the number of personnel on the base, and dictate how heavily used support infrastructure is needed.

Deliverables	
Data shall be collected in the forms of maps, facility inventories, equipment lists, operating procedures, projected sea level rise, and historic storm and/or flooding events.	Sea Level Rise, Storm Surge, and Flooding Scenario Maps
	Inventory and Critical Information List of all Infrastructure and Facilities
	Installation Utility Plans
	Financial Budgets for Maintenance and Capital Improvements
	Installation Land Use and Environmental Plans
	Current Building Codes and Policies
	List of Tenant Commands, Mission, Critical Operational Assets, Facility Requirements
	List of Support Services
	Installation and Tenant Command High Level Operational Schedule

4.6.4 STEP 4: Exposure and Vulnerability Analysis

Goal: Once data is collected, it must be reviewed holistically to identify the areas and infrastructure most exposed to risk. Hazard exposure analysis identifies the natural and technological hazards to which the community is exposed and assesses the specific locations that would be affected by different intensities of impact (Lindell et al. 2006). Vulnerability addresses the actual physical infrastructure and/or social elements vulnerable to sea level rise, coastal storm surge, or flooding. Physical vulnerability occurs when buildings and infrastructure are built with inadequate construction and/or materials that cannot withstand structural or elemental stresses. Social vulnerability has been defined in terms of people's capacity to anticipate, cope with, resist, and recover from the impacts of a natural hazard (Blaikie et al. 2004). In a military context, this is a command's ability to maintain readiness during and after a storm or flood event, considering military commands consist of people who must work cohesively in order to accomplish tasks.

Tasks:

Physical Factors

- Analyze sea level rise, storm surge and/or flood maps in comparison with facility, infrastructure, and utility systems locations, in order to generate a list of the physical elements exposed to risk.
- Based on existing facility conditions and operational uses, prioritize the list of exposed facility, infrastructure, and utility systems in order of most vulnerable to least vulnerable. Items to consider also should be annual maintenance costs, replacement value, and co-dependency of one infrastructure system with another.
- Identify environmental areas that are sensitive to risk, and require preservation and/or prevention of future development.

Operational Factors

- Compare mission and operational requirements/scheduled with the facility, infrastructure, and utility systems locations at risk identified above, generate a list of facilities that are most exposed from a physical and operational risk of performance.
- Operational Commanders must assess how their ability to perform will be threatened not only to physical damage to their workspaces, but due to weakened readiness as sailors homes, families, and support services are damaged.

Deliverables	
Collected data shall be reviewed in coordination and analyzed for exposure and vulnerability. Physical infrastructure and environmental conditions shall be reviewed against operational and personnel requirements.	List of Exposed and Vulnerable Facilities and Infrastructure
	List of Exposed and Vulnerable Environmental Areas

4.7 Adaptation Selection: Step 5-6

Military facility engineers having first acknowledged sea level rise, storm surge and coastal flooding are a threat to their installations, and secondly performing a risk assessment of their installation, can have confidence in selecting an adaptation strategy to further study, design, and implement. Coastal facility managers are often overwhelmed with the vast information available for adaptive design and planning strategies, and feel pressured to make quick decision without a clear understanding of all options (Langridge et al. 2014). With limited funding resources, and demanding operational requirements on Naval installations, decisions become high profile agendas, which must be based on sound criteria and evaluation. Coastal Managers in the selection process must first manage, balance, or choose to reduce risk based on the lists of exposed or vulnerable facilities, infrastructure, or environmental areas as generated in Step 5 of the Adaptation Evaluation Framework.

Once prioritized lists of facilities or infrastructure at risk are created, then the process of selecting the most appropriate adaption strategy can be completed. By using the *Protect, Accommodate, or Retreat: Spectrum of Adaptation Strategies* matrix below, coastal and military facility engineers can have confidence in evaluating, comparing, and selecting an adaptation response. Once chosen, a detailed design with a qualified architect and engineer can be pursued with assurance. Coastal managers gain confidence by fully understanding the benefits, concerns, costs, time, maintenance, and resiliency qualities of each system, and then evaluating those qualities against the physical and operational requirements of the installation.

4.7.1 STEP 5: Managing, Balancing, or Reduction of Risk

Goal: Once risk is understood physically and operationally, decisions can be made to accept or reduce risk depending on the severity of risk. Once the risk assessment has been completed, the installation can either ignore the risk or decide to manage it by (1) controlling processes and behaviors that generate new risks (for example, through better zoning and enforcement of building standards); (2) reducing existing risk (for example, through infrastructure strengthening; or (3) preparing for an event (for example, through contingency planning and the strengthening of installation policies and practices) (Dickson et al. 2012). Managing risk by accepting certain forms of risk, may be an acceptable option once risk is looked at holistically and funding is evaluated. The areas and infrastructure identified as having the greatest risk to human health, infrastructure longevity, and operational readiness should be chosen to reduce risk first. Although the focus of this paper is the reduction of risk by infrastructure adaptations, overall installation risk also can be reduced by implementing and emergency management procedures that are human induced. Ultimately resiliency is a combination of both physical and human measures.

Tasks:

Physical Factors

- Based on the most vulnerable to least vulnerable infrastructure list, identify which facilities or infrastructure must be upgraded in the short, mid or long term.
- Identify which facilities or infrastructure based on their risk assessment, command leadership is willing to accept risk on.
- Identify which environmental areas must be preserved through adapatation measures, which can accept degradation, and what areas must land-use practices be implemented to alter development.
- Update building codes and land-use plans.

Operational Factors

- Based on the most vulnerable to least vulnerable operational requirements, identify which activities must be sustained at all times, even during natural disaster events. Which activities are secondary, and can have brief periods of inactivity.
- Which support services must be sustained at all times, how can command support serve to increase resiliency even during lapse of some support services for sailors and families.

Deliverables	
Risks shall be evaluated against personnel safety, operational requirements, and costs to determine the level of risk that is acceptable to maintain.	Prioritized List of Exposed and Vulnerable Facilities and Infrastructure With Adaptation Timeline
	Prioritized List of Exposed and Vulnerable Environmental Areas with Adaptation Timeline
	Updated Building Codes and Installation Land-use Plans
	List of Facilities, Infrastructure, Missions, and Support Services That Will or Will Not Accept Risk

4.7.2 STEP 6: Adaptation Selection

Goal: With clear balanced priorities in place, physical adaptation strategies shall be explored and chosen by comparing physical and operational resiliency objectives against the environmental and built infrastructure resiliency qualities. Although increased resiliency is the primary goal of coastal managers, the framework also allows benefits, concerns, cost, time, and maintenance factors to be evaluated in the final decision.

Tasks: After understanding the areas or key pieces of infrastructure at risk, coastal managers shall answer the questions below, and shall use the answers to the questions to help select the best adaptation strategy as presented in the *Protect, Accommodate, or Retreat: Spectrum of Adaptation Strategies* matrix.

Question 1: What is the contextual application?

Port or Pier-Infrastructure supports maritime operations, and require a deep berth, mooring, and support utilities.

Built Infrastructure- Infrastructure or a complex of facilities are present, require a firm foundation, and must remain in a fixed location.

Individual Facilities- A facility is present, requires a firm foundation, and must remain in a fixed location. Due to the structural and material quality of the facility, it is vulnerable to water intrusion and/or extreme waves.

Harbor Entrance- An open body of water that serves as an entrance to a harbor, marina, or protected inland area of water.

Coastal Shoreline- A shoreline that is exposed to an open body of water, specifically the ocean or large bay, that experiences tidal fluctuations, current, and waves.

Inland Shoreline-A shoreline that is connected to an open body of water, specifically a river, bay, estuary, or wetland, but is protected from large waves from the open ocean.

Question 2: Is a strong delineated shoreline required or can the shoreline be organic in form.

Are upland facilities such as a port, pier, or existing infrastructure fixed in their position and thus require a delineated shoreline, or is there a significant buffer between the shore and upland facilities, in which a more organic adaptation strategy could be employed?

Are their operational requirements that require a deep berth for ships, amphibious landings, or maritime traffic?

Is the shoreline experiencing erosion, or is it stable in nature?

Question 3: What are the conditions of the water?

Is the shoreline connected to an open body of water, or is it a protected body of water?

Is the shoreline subject to pounding waves, currents, and large tidal fluctuations, or is the water body calm in nature?

Question 4: What are the budget implications?

Are there funds available for sustainment, restoration, or maintenance?

Will there be funding available for annual maintenance or upgrades?

Is there time to address the risk, and seeking MILCON appropriations are a viable option?

Can this project be linked with another project currently planned?

Question 5: What are the time horizons for implementation and how long will the adaption measure need to be in place?

Is the threat of sea level rise imminent and coastal flooding imminent, or is the risk several decades out?

Are these facilities scheduled for replacement or future upgrades already?

Is this solution intended for decades (20-50 years), or are there future infrastructure or operational requirements that will change the use along the shoreline?

Question 6: What are the maintenance implications of the adaption strategy?

Is there staff on hand to perform preventative maintenance if required, and do they have the skill set to operate the adaptation strategy if needed?

Question 7: Is preservation and protection of the environment a primary concern?

Are there Federal or State Regulations that protect or require a certain portion of the shoreline line to remain in a natural form?

Aesthetically does the shoreline serve a specific need or benefit?

Does the shoreline provide recreational, training, or operational requirement such as amphibious landings?

Is there willingness to explore alternative resiliency strategies that utilize the co-benefits of natural ecosystems?

Question 8: What is the current level of risk, and is the built form in either physical or natural terms required to counter a large or small risk that threatens operational and/or human resiliency?

Are operational requirements so high, that there can be no operational disturbances or down time?

Is there great historic value in the shoreline or built asset?

Is there great human welfare and safety at risk because of the vulnerability?

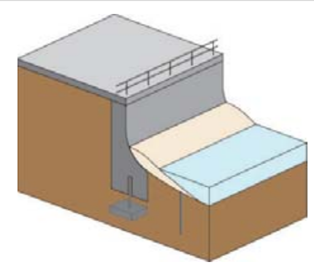
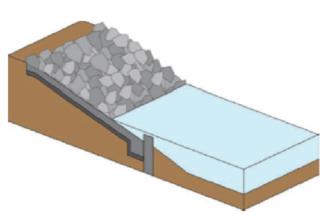
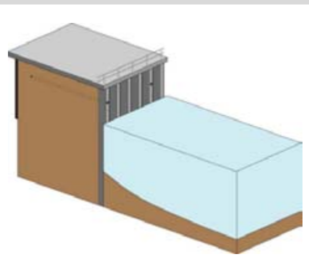
TABLE 5: PROTECT, ACCOMMODATE, OR RETREAT: SPECTRUM OF ADAPTATION STRATEGIES

For Sea Level Rise, Storm Surge, and Coastal Flooding

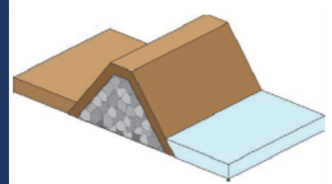
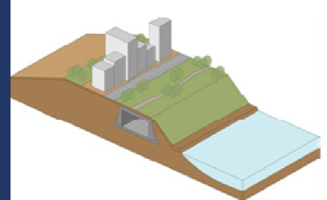
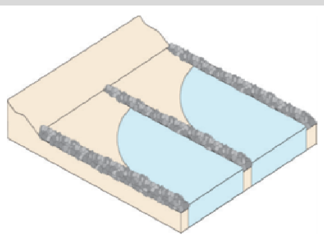
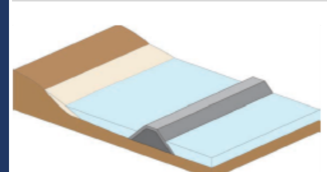
Caponigro 2017

PROTECT

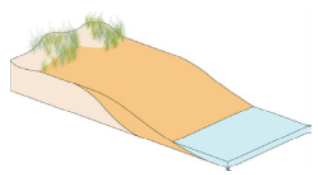
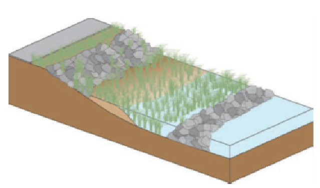
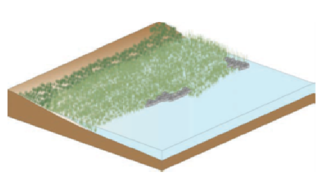
Structures, infrastructure, assets, and human life are protected from the intrusion of water, tidal flooding, shore erosion, or damaging effects of strong waves and storm surge. Protection is viewed through two lenses, either "hard" or "soft" measures. Hard measures use physical structure, engineering, and create defined lines between the sea and land. Soft measures employ nature-based strategies, and the line between where the water and land begin is blurred.

Strategy	Contextual Application	Overview	Benefit	Concern	Cost	Time	Maintenance	Environmental Impact	Built Robustness
Seawall									
 Image-NYC Department of Planning 2013a	Port and Pier Built Infrastructure	Hardened structures that make a delineated line between the sea and land.	Withstands strong waves and storm surge, while protecting upland infrastructure from flooding and sea level rise.	Passive erosion and disruption of natural habitat.	High	Long Lasting	Regular Maintenance and Reinvestment	High	High
Revetment									
 Image-NYC Department of Planning 2013a	Built Infrastructure Coastal Shoreline	Hardened structures that reinforce the bank along the shoreline with a strong delineated line. Built to withstand pounding waves.	Protects valuable infrastructure against pounding waves and storm surge. Prevents shoreline erosion, some opportunity for alternative habitat.	Disruption of natural habitat and shoreline squeeze. Rising seas can overtop.	Low-Medium	Long Lasting	Low Maintenance and Reinvestment	Medium	Medium-High
Bulkhead									
 Image-NYC Department of Planning 2013a	Built Infrastructure	Hardened structures that reinforce the bank along the shoreline to protect from coastal erosion.	Prevents upland bank and shore erosion from slowly rising seas and small wave action.	Not constructed to protect against strong storm surge, or continual pounding waves. Disruption of natural habitat.	Medium	Long Lasting	Regular Maintenance and Reinvestment	High	Low-Medium

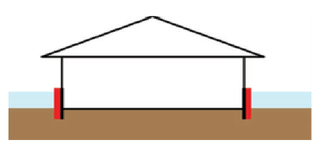
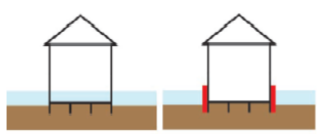
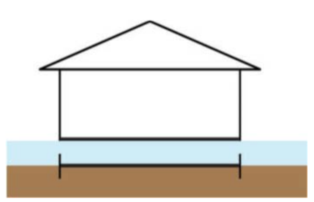
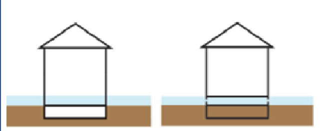
PROTECT (Continued)

Strategy	Contextual Application	Overview	Benefit	Concern	Cost	Time	Maintenance	Environmental Impact	Built Robustness
Levees and Multipurpose Levees									
 	Built Infrastructure Inland Shorelines	Traditional levees are earth formed embankments that separate the sea or a river from the land. Multipurpose levees have the same characteristics as a traditional levee, but incorporate reinforced structure to support other infrastructure services.	Protects valuable inland infrastructure from coastal flooding and sea level rise. Berms can be incorporated into upland infrastructure or can be designed to incorporate park or recreation. Often used in areas where upland elevation is below sea level.	Not constructed to protect against strong storm surge, or continual pounding waves. Disruption of natural habitat. Expansive and take a wide area of land.	High	Long Lasting	High Maintenance and Reinvestment	High	High
Groin									
 Image-NYC Department of Planning 2013a	Harbor Entrance Coastal Shoreline	Hardened structures perpendicular to the shoreline to protect against dominating tangential wave patterns.	Built to withstand erosion that occurs by sand and sediment drift along the shoreline.	Downdrift beach has increased vulnerability due to the weakened resiliency and width of the beach. Beach nourishment required.	High	Long Lasting	Regular Maintenance and Reinvestment	High	Low-Medium
Breakwaters and Floating Breakwaters									
 Image-NYC Department of Planning 2013a  Image-NYC Department of Planning 2013a	Offshore	Traditional breakwaters are hardened off shore structures to break strong waves, and allows dissipated waves to reach the shoreline. Floating breakwaters are similar to traditional breakwaters but rise and fall with the tide.	Protects shoreline against pounding waves. Removed from the shoreline, which allows ecosystem functions to remain in place, or protects hardened infrastructure such as seawalls or bulkheads from increased wave action.	Does not protect against sea level rise. Fixed breakwaters can become submerged during high-tide, which is a boating hazard.	Medium-High	Long Lasting	Regular Maintenance and Reinvestment	Medium	Medium

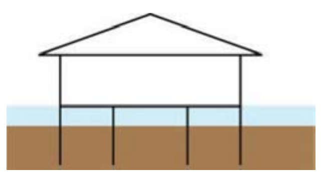
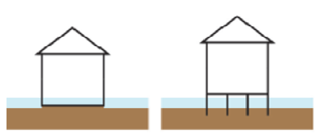
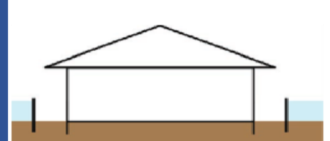
PROTECT (Continued)

Strategy	Contextual Application	Overview	Benefit	Concern	Cost	Time	Maintenance	Environmental Impact	Built Robustness
Beach Nourishment									
 Image-NYC Department of Planning 2013a	Coastal Shoreline	Shorelines provide a natural buffer for coastal waves and flooding. Sand along with native plantings are added to the shoreline to reinforce the natural structure. Often used in coordination with other strategies.	Prevents upland bank and shore erosion from slowly rising seas and small wave action by utilizing natural and native materials. Maintains recreation and wide beach buffer.	Can disrupt shoreline ecosystem during replenishment. Not a one time effort, must be replenished as erosion occurs.	Low	Short Lasting	High Maintenance and Reinvestment	Medium	Medium
Living Shoreline									
 Image-NYC Department of Planning 2013a	Coastal Shoreline Inland Shoreline	Address erosion in areas of lower waves, by dissipating waves into strategically located vegetated shoreline habitats and incorporate ecological functions to better protect the shore.	Protects shorelines from increased erosion and gradual sea level rise, while also improving localized water quality and the ecosystem. Visually attractive.	Not appropriate for areas with high-energy wave action or where a defined hardened edge is require.	Low-Medium	Long Lasting	Low-Medium Maintenance and Reinvestment	Low	High
Constructed Wetlands									
 Image-NYC Department of Planning 2013a	Inland Shoreline	A newly built or restored wetland, that uses soil and natural plantings to filter water, create wildlife habitat, and serve as a buffer for coastal storm surge and inundation.	Protects shorelines from increased erosion and gradual sea level rise, while also improving localized water quality and the ecosystem. Visually attractive.	Not appropriate for areas with high-energy wave action or where a defined hardened edge is require. Requires expansive space.	Medium	Long Lasting	Low-Medium Maintenance and Reinvestment	Low	High

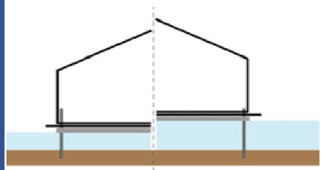
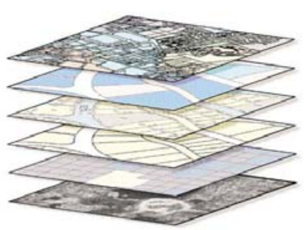
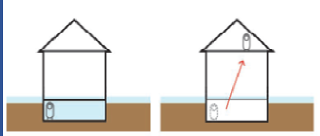
ACCOMMODATE Accommodation acknowledges that the sea level is rising and floods will occur, but changes the way humans and the built form responds, instead of attempting to control the inundation of water. Change can occur by changing the building envelope, or by elevating a structure to allow water to flow beneath the structure.

Strategy	Contextual Application	Overview	Benefit	Concern	Cost	Time	Maintenance	Environmental Impact	Built Robustness
Dry Floodproofing									
 Image-NYC Department of Planning 2013a  Image-NYC Department of Planning 2013a	Built Infrastructure Individual Facilities	New Construction: The building structure (materials and penetrations) is designed to withstand water infiltration and loads. Existing Construction: The building is retrofitted to seal all penetrations and exterior walls and foundation may need to be reinforced to counter hydrostatic loads.	Provides protection from storm surge and flooding waters that can damage valuable equipment and materials within a facility. Allows for the use of space at or below grade that typically would have been reserved for parking, access, or storage.	Can create a false sense of security, and should be used in combination with sound interior design and elevation of critical assets within a facility. If deployable flood barriers are utilized, this requires humans to physically place the structure in anticipation of a flood. If materials are exposed to sustained water, may need to be replaced.	Medium	Medium Lasting	Regular Maintenance and Reinvestment	Medium	High
Wet Floodproofing									
 Image-NYC Department of Planning 2013a  Image-NYC Department of Planning 2013a	Built Infrastructure Individual Facilities	New Construction: First floor finished grade is built above the designed flood level. Void below allows free passage of water, which allows the system's hydrostatic pressure to equalize. Existing Construction: The building is retrofitted to allow water to flow through ground level spaces uninhabited. Finished spaces are raised above the designed flood level.	Building materials resistant to water damage. Viable option for garage or warehouse type spaces where valuable materials or equipment can be placed on overhead shelves, catwalks, or 2nd level floors in anticipation of a flood. If adequate storage is not available onsite, then additional contents can be relocated offsite.	Can create a false sense of security, and should be used in combination with sound interior design and elevation of critical assets within a facility. Wet floodproofing is not intended to be a solution for long-term flooding, since prolonged exposure to water can damage materials.	Low-Medium	Medium Lasting	Regular Maintenance and Reinvestment	Medium	Medium

ACCOMMODATE (Continued)

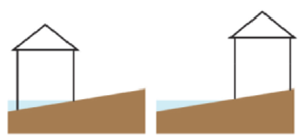
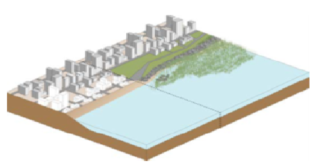
Strategy	Contextual Application	Overview	Benefit	Concern	Cost	Time	Maintenance	Environmental Impact	Built Robustness
Elevate									
 Image-NYC Department of Planning 2013a  Image-NYC Department of Planning 2013a  Image-NYC Department of Planning 2013a	Built Infrastructure Individual Facilities	Mound New Construction: Additional fill will be added to the site, so the entire facility's structure will be placed above the flood and mean high water level. Pier New Construction: The entire facility's structure will be placed on columns or piers, so the final first floor level will be above designed flood height and mean high water level. Piers Existing Construction: The building will be elevated with columns or piers so the final first floor level will be above designed flood height and mean high water level.	The entire area surrounding the foundation of a facility or the facility itself is raised in order to accommodate the designed flood level , and can be raised to accommodate future sea level rise and mean high tide levels. All habitable and storage spaces of the facility are located above the threat of water, ensuring preservation of life and property. This ensures minimal site cleanup after a storm event.	Major construction efforts are required in regrading a site, as well as driving piles, which requires specialized equipment and engineering to ensure soils have the bearing capacity. Based on the density of the area and actual site dimensions, grading may not be an option, and raised structures on piers may appear out of context with adjacent facilities.	Medium	Long Lasting	Low Maintenance and Reinvestment	Medium	High
Floodwalls									
 Image-NYC Department of Planning 2013a	Built Infrastructure Individual Facilities	The use of permanent or removable floodwalls strategically placed around a site to counter occasional flooding and storm surge.	Counter periodic flood events or storm surge, and are strategically placed to hold out rising waters. Can be designed to coordinate into existing facilities or landscaping. Can double as a security measure.	Failure concerns because of inability for a structure to withstand sliding, overturning, or hydrostatic pressure of water. Deployable floodwalls must be installed by human action.	Medium	Medium-Long Lasting	Regular Maintenance and Reinvestment	Medium	Medium

ACCOMMODATE (Continued)

Strategy	Contextual Application	Overview	Benefit	Concern	Cost	Time	Maintenance	Environmental Impact	Built Robustness
Floating Structures									
 Image-NYC Department of Planning 2013a	Port and Pier Built Infrastructure	A floating structure floats on the water permanently, and rises and falls with the change of the tide.	Floating structures can rise and fall with changes in tide conditions, and with adequate piles, can withstand storm surge levels as well. With adaptable transition connectors, shore based utilities can rise and fall.	Vulnerable to large waves, and should be placed in sheltered water bodies	High	Long Lasting	Regular Maintenance and Reinvestment	Medium	High
Planning Regulations and Tools									
 Image-PMM 2015	Built Infrastructure Individual Facilities Coastal Shoreline Inland Shoreline	Planning regulations create a framework to organize development in coordination with community resiliency goals, while also taking into consideration the environment and safety of humans.	A strong vision and commitment to sea level rise, storm surge, and coastal flooding adaptation will create clear guiding principles for a planning department and empowers staff to make educated decisions.	Complacency can occur if regulations are not reviewed with the existing conditions on the ground and the dynamic changes of sea level rise, storm surge, and flooding.	Low	Long Lasting	Regular Maintenance and Reinvestment	Low	High
Essential Systems and Equipment- Assessment and Action									
 Image-NYC Department of Planning 2013a	Built Infrastructure Individual Facilities	Assess essential systems, equipment, auxiliary parts, and the codependency of these systems. Strategic measures are then implemented to reduce exposure to risk and increase resiliency.	Sometimes it is not feasible to protect or relocate a whole facility, instead just the essential pieces of equipment can be assessed and then addressed by relocation, floodproofing, elevation, anchoring, or building in redundancy.	If the codependency of services is not understood then one essential service may be damaged if another was not a part of the adaptation strategy	Low-Medium	Long Lasting	Regular Maintenance and Reinvestment	Low	High

RETREAT

Retreat allows the shoreline to erode or interface with the rising sea in naturalized processes. This strategy ensures no new development will take place within a designated retreat zone, and if development is allowed, those structures shall be built with the anticipation of eventual abandonment when required.

Strategy	Contextual Application	Overview	Benefit	Concern	Cost	Time	Maintenance	Environmental Impact	Built Robustness
Strategic Retreat									
 Image-NYC Department of Planning 2013a  Image-NYC Department of Planning 2013a	Built Infrastructure Individual Facilities	Strategic retreat is the process of removing infrastructure and development from areas vulnerable to sea level rise and flooding. Future development is not allowed in the retreat zone, and relocation of existing facilities and infrastructure is assessed based on operational requirements.	Risk and exposure is reduced significantly against coastal hazards, since future development is completely removed from the exposure zone. Shorelines are able to move gradually inland, allowing ecosystems to adapt. Upland structures out of the exposure zone may not have to incorporate other adaptation strategies for infrastructure.	Special consideration must first take place on where development will transition to, what will happen to existing development (will it be demolished or relocated), and what will remain in the vacant area. Who pays for relocation efforts.	High	Long Lasting	Low Maintenance and Reinvestment	Low	High

Deliverables	
Adaptation strategies shall be explored and chosen.	Adaptation Strategies Identified with Preliminary Budgets for Facilities and Infrastructure
	Adaptation Strategies Identified with Preliminary Budgets for Environmental Areas

4.8 Implementation: Step 7-8

During the implementation phase, coastal managers must take all the knowledge gained on risk, decisions made about adaptation strategies, and systemically put those strategies into practice. A clear implementation plan must employ a project timelines, who is responsible for each action during design and construction, and how the project will ultimately be funded. Complete adaption will not be quick for a large installation with numerous facilities and pieces of infrastructure; instead, adaptation should be viewed as an ongoing effort, that must be systematically incorporated into each year's sustainment, restoration, and modernization (SRM) budget, and within each year's new construction budget.

Implementation also requires that coastal managers step back periodically to assess how the program is working, analyze if adaptation strategies are working as intended, reassess if risk has changed or evolved, and review current operational and personnel requirements to ensure adaptation strategies are still in line with the installation's mission. Additionally sea level rise, storm surge, and flooding are dynamic, it is important that coastal managers and facilities engineers continue to educate their selves on emerging science and new technologies for adaptation. Finally, although the focus of this paper is on infrastructure and facility resiliency, overall installation resiliency requires that emergency action plans to respond to coastal natural disasters are reviewed, updated, and practiced yearly. Emergency management falls under the installation commanding officer's purview, but public works staff are a critical support element within the emergency management team, and must ensure they participate in ongoing training, and should provide feedback on procedures and risk that are related to infrastructure and facilities.

4.8.1 STEP 7: Implementation

Goal: Projects are developed with clear schedules, assigned project managers, and funding streams are identified. Leadership reviews progress regularly and how holds project managers accountable for implementation and project coordination. If challenges occur during planning, design or construction phases, project managers seek assistance from the leadership chain to ensure projects remain on schedule and within budget. Policies and procedures to reduce risk can also be implemented through nonphysical strategies, such as creating emergency operation plans, disaster response teams assembled, and ongoing training conducted to ensure personnel, both emergency responders and installation personnel know how to respond. Resiliency is increased by not only implementing long-term measures of physical resiliency against sea level rise, but by putting procedures in place to counter storm surge or flooding in short term periods.

Tasks:

Physical Factors

- Assign a Project Manager for each adaptation project, who is empowered to make decisions on design and construction details, and is committed to keeping leadership informed on project status and schedule.
- Develop a planning, design, and construction schedule.
- Develop a realistic project estimate, explore funding options, and seek funding. Can the project be incorporated into other planned projects?
- Ensure feedback mechanisms on project status are in place for leadership and project team.
- Explore acquisition strategies to ensure the most qualified contractors are selected for design and construction.

Operational Factors

- Review, update, or create if necessary emergency operation plans at the installation level and command level[19]. Ensure sections that focus on storm surge and flooding are included, and are viewed from a physical and social resiliency perspective.
- Ensure Emergency Management Team understands current adaptation project's timelines and scope. New projects may alter how the rest of the Emergency Management Team operates or plans for future emergency scenarios.
- Identify and conduct regular training for disaster response personnel. Hold periodic drills and exercises to practice response procedures.
- Identify and train installation and command personnel on emergency communication procedures and the chain of command during an emergency event.

Deliverables	
Adaptation projects have an assigned project manager and team who are committed to identifying clear tasks, schedules, and funding in order to get projects completed. Installation Emergency Management Plans are current and responsive to risk.	Project Manager and Team Assigned
	Project Schedule and Definable Tasks Developed
	Project Estimate and Funding Identified
	Updated Installation Emergency Managment Plans
	Regular Training for Emergency Management Team, to Include Chain of Command and Communication Strategies

[19] Each naval installation has an Emergency Management Officer that coordinates the emergency management response team for the Commanding Officer. In the event of an actual emergency, the Emergency Management Officer and Command Duty Officer are responsible for standing up the Emergency Operations Center (EOC). The EOC coordinates all emergency response actions, and is responsible for keeping the Commanding Officer and Regional Operations Center aware of activities. Several people and support departments are a part of the response team, and that is why it is critical to have ongoing training and drills to ensure a cohesive response.

4.8.2 STEP 8: Monitor and Review

Goal: Adaptation strategies are monitored for their success in creating resiliency and reducing risk, and altered if not performing well or if risk has changed. Priority lists for adaptation are reevaluated to determine if risk persists, and new risks are identified if applicable.

Tasks:

Physical Factors

- Update infrastructure and facility adaption priority lists. Revaluate and secure funding for implementation in coordination with yearly budget.
- Educate planning and design staff on new adaptation technologies, and current local sea level rise, storm surge and flooding science.

Operational Factors

- Evaluate operational readiness, and how support infrastructure and facilities are supporting installation mission sets.

Deliverables	
Adaptation strategies are monitored for their success in creating resiliency and reducing risk, and altered if not performing well. New risks are identified if applicable.	Updated Prioritization and Adaptation List for Exposed and Vulnerable Facilities and Infrastructure

5. DISCUSSION

5.1 Findings

The question explored in this thesis was- *How can coastal military facilities engineers increase resiliency on military installations throughout the United States, by evaluating and applying a set of adaptation design and planning principles to best adapt to climate change as applied to sea level rise, storm surge, and flooding.* Through the use of grounded theory and a wealth of existing scientific and practical knowledge, this thesis resulted in the development of an Adaptation Evaluation Framework for Sea Level Rise, Storm Surge, and Coastal Flooding that coastal military facilities engineers can use to increase resiliency against climate change and specifically sea level rise, storm surge, and coastal flooding by first understanding the inherent risk unique to their installation, second by choosing an adaptation strategy best suited for their risk, and finally by executing a strong implementation plan.

Resiliency as demonstrated in this thesis is not a one-strategy solution, but instead is a multi-pronged process that empowers all stakeholder involvement, and views resiliency as a component of not only built terms, but also operational terms. Operational resiliency is achieved by first ensuring support infrastructure that serves ships, planes, and administrative spaces are adapted to sea level rise, storm surge, and coastal flooding, thus allowing those essential mission sets of the Navy to perform, and second by ensuring installation personnel are involved in the process and execution of emergency preparedness and response against coastal natural hazards.

5.2 Benefits of the Adaptation Evaluation Framework

A sub question of this thesis was- *With a number of competing interests and data available, what is the most effective method of analyzing and applying a design strategy on each coastal military installation?* This thesis demonstrates a strong foundation of unified data to make educated adaption design and planning choices, can be assembled by applying a systematic framework that first assesses risk, considers installation mission objectives, and then objectively balances risks with stakeholder involvement. This unified data is then compared with the *Protect, Accommodate, or Retreat: Spectrum of Adaptation Strategies* matrix in order to choose confidently the best design or planning strategy considering the specific infrastructure or facility risk present.

In the implementation phase, not only are current adaptation projects evaluated on how they increase resiliency, but also those projects placed on the shelf during the balancing step can be reevaluated for inclusion on updated adaptation priority lists or incorporated into new projects in the planning phases. Ultimately risk and in return resiliency, is not a stagnant condition, both must be evaluated periodically as each installation evolves in time. As the intended users of the evaluation framework, Naval Public Works Departments and their facilities engineers have numerous competing requirements throughout each fiscal year. By having a prioritized list of vulnerable facilities, infrastructure, and environmental areas as completed in Step 5 of the evaluation framework, and then monitoring and reassessing that list in Step 8 of the evaluation framework annually, this will keep facilities engineers engaged in maintaining and increasing resiliency to sea level rise, storm surge, coastal flooding.

5.3 Funding- Making Adaptation a Reality

As demonstrated in the *Adaptation Evaluation Framework* adaptation action is achieved through the implementation phase, but to realistically make adaptation achievable Public Works Departments must ensure projects are included in their annual Capital Improvements Plans (CIP) and Maintenance Execution Plans (MEP), and that Public Works leadership is aggressively attempting to secure funding. All the extensive research, planning, and design that takes place for an adaptation strategy is merely an exercise, without placing priority on the projects by including them in an approved and working CIP or MEP. By including the projects in the CIP and MEP it validates to installation level leadership that these projects are valuable, and demonstrates to higher chain of command they will be executed with an intended schedule and that funding is essential for this requirement. Funding is the final sub-question that this thesis addresses- *With limited funds, how can adaptation design strategies be implemented into capital improvement plans and maintenance execution plans incrementally, increasing resiliency steadily?*

5.3.1 The Challenges of Funding

In the challenging fiscal times our military is operating in, it unfortunately means not all risk can be eliminated due to the shear cost. Conversely though, when risk is evaluated against current infrastructure conditions, and installation mission requirements, adaptation and resiliency can be managed by first addressing the most vulnerable or exposed infrastructure, and then secondary risks can be addressed at a later time through adaptation measures.

Risk assessments, prioritized maintenance lists, and capital improvement plans also ensure that funding will be spent in the most effective and efficient way. Although investment in adaptation can be a large undertaking financially, innovative Public Works Officers and NAVFAC planning staff can be creative with their budgets, by investing in adaptation strategies that are linked to funds already established for regular maintenance or planned facility/infrastructure upgrades. New projects that are identified in CIP's can incorporate sea level rise projections, storm surge, and or flooding scenarios into their design in the beginning stages. Ultimately, early and systematic investment in adaptation will save money in the long run, because the cost to completely re-build damaged facilities and infrastructure that failed to adapt can be a major lump sum expense.

The chart below developed by The World Bank identifies the build back costs for infrastructure that is damaged due to a natural disaster. Although it may appear that some categories do not apply to a military installation, such as housing, schools or hospitals, this is actually not the case. Naval installations are similar to small cities, and often are comprised of not only of industrial or transport types of facilities, but also support infrastructure such as housing complexes, administrative spaces, highly complex communication facilities and utility systems. In all cases the build back factor is over one, and this does not even consider the cost to demolish the existing facility or infrastructure. If a coastal storm or flood damages large swaths of infrastructure on an installation, the existing Sustainment, Restoration, and

Maintenance (SRM) budget will not be able to accommodate such a large expense and an Emergency Military Construction (MILCON) will have to be pursued. The maximum amount that the Secretary[20] may obligate in any FY under "emergency construction" authority is $50 million (DON 2014), and although the authority may be there, the funds must be taken from the Secretary's budget that may have been reserved for other projects.

Table 6: The Costs of Building Back Better After a Disaster
(Adapted from The World Bank 2013)

Sector	Build Back Better Factor
Housing	1.10-1.35
Schools	1.10-1.50
Hospitals	1.10-1.50
Agriculture/Livestock Infrastructure	1.10-1.40
Industrial Facilities	1.10-1.40
Commerce and Trade	1.10-1.35
Water and Sanitation	>1.00*
Transport	>1.00*
Electricity	>1.00*
Communications	>1.00*

Note: Costs of building back better = Replacement Costs x Building Back Better Factor and Building Back Better Factor = Costs of Quality Improvements + Technological Modernization + Relocation to Safer Areas (if needed) + Disaster Risk Reduction Standards + Multiannual Inflation

* Factors for infrastructure sectors vary highly depending on the choice of reconstruction.

5.3.2 Capital Improvements Plans

The first option to fund adaption strategies is to place a project in the annual CIP. The Navy defines capital improvements as any new construction that exceeds $1 million dollars in construction costs. Projects that exceed 2 million dollars are considered Military Construction (MILCON) and are required to first be authorized by Congress, and then funds appropriated in a specific year by Congress to fulfill the

[20] Secretary refers to the Secretary of the Navy (SECNAV) who is the senior civilian leader of the Navy, and is responsible for all affairs of the Department of Navy.

requirement. Once a project's funds are appropriated, the Navy has 5 years to obligate funds and start construction. Funds that are not used on an obligated project after 10 years, are collected and unavailable for use on that specified project. Each year the Navy completes the Program Objective Memorandum[21] (POM) process, in which each installation sends up their prioritized list of MILCON projects to their assigned NAVFAC Facilities Engineering Command (FEC). Each FEC's local leadership collates, shuffles, and restacks their prioritized MILCON list, which is then vetted through the FEC's regional command (NAVFAC Atlantic or NAVFAC Pacific) for prioritization at a regional level. These prioritized lists are sent to NAVFAC Headquarters, and then the collated into one prioritized list for all Naval MILCON facilities. This list is sent to Commander Navy Installations Command, forwarded to the Secretary of the Navy, and then presented by the Secretary of Defense for approval to Congress. Ultimately, all Naval MILCON's are competing for funding against Department of Army and Air Force MILCON's also.

As demonstrated above, with 70 Naval installations throughout the World, and limited funding from Congress, it is very challenging and time consuming to get a project approved. This challenge coupled with the current policy which Congress has asserted, that no projects for the sole intention of adapting to climate change will be funded, creates great uncertainty for installation level planners and Public Works Officers. Typically, projects that are closely linked to direct support of ships, planes, or specials operations are much more likely to be approved by Congress due to their direct and tangible link to operations, while utilitarian infrastructure or facilities do not present the same appeal. Due to this challenging process, Public Works Officers and FEC Commanding Officers must ensure the MILCON projects they are requesting are soundly developed, are able to also demonstrate their direct link to Naval operational mission sets, and may need to not classify the project as a climate change adaptation, but instead demonstrate how the project is directly related to operational requirements.

[21] The final product of the programming process within the Department of Defense, the Components Program Objectives Memorandum (POM) displays the resource allocation decisions of the Military Departments in response to and in accordance with Quadrennial Defense Review (QDR) and Defense Programming Guidance (DPG) (DOD 2008).

The POM sent up each year has hundreds of MILCON projects that the Navy prioritizes for requested authorization over the following 5 years, with the intention that the following fiscal year projects will only be funded that year, while the other projects are shown to Congress as a foreshadowing of future year needs. Congress can choose to restack and choose which projects they see fit, while also balancing not only the needs of the Navy, but the entire Defense Department. This rack and stack game, makes it very challenging for Public Works Staff to plan effectively for adaptation in short term manner. That is why it is critical that Public Works staff are innovative by either linking an adaptation strategy to an existing MILCON project in planning, or by demonstrating that if a stand-alone adaptation MILCON is not funded, then major operational readiness will be threatened. Due to this intensive review process, and the threshold of what is considered capital improvements, major adaption projects such as a seawall, floating pier, or levee for example would be appropriate for a standalone project, while utilities that are susceptive to flooding, and also support a new facility, may be a good option to relocated or upgrade as part of a proposed project that may not directly be linked to sea level rise.

Local CIP's typically project 5 years out with a high level of detail for each project, including a developed scope and project estimate. Locally the benefits of A CIP ensures that reinvestment is done in a smart and efficient way for infrastructure/assets, also allows time for design, securing funding, time to find/secure sites, and creates development in a planned method (Marlowe, Rivenbark, and Vogt, 2009). For Congress and higher naval leadership it shows how planning saves money, creates smart growth, and that project requests have been vetted and are true requirements.

5.3.3 Maintenance Execution Plans

The second strategy local installations have to fund and execute adaptation is through their Maintenance Execution Plans (MEP) or sometimes referred to as Maintenance Action Plans (MAP), both have the same intention. Each naval installation has an annual public works Operations and Maintenance (O&M) budget that is funded through O&M funding that is divided into Sustainment, Restoration, or Maintenance (SRM) special interest code (SIC) lines of accounting, see Table 7 below. These funds are to provide for regular maintenance and modernization on facilities and infrastructure. O&M funds are provided in a specified fiscal year, and must be spent or (obligated) in the same fiscal year. The funds on an obligated project expire after 6 years.

Minor construction projects non-MILCON funded, are available from O&M funding, and must be spent to carry out an unspecified minor military construction project costing not more than 1 million dollars. If the cost of the project is above $1 Million, but does not exceed $3 million, or $4 if intended solely to correct a deficiency that is life threatening health threatening, or safety-threatening, then the House Armed Service Committee (HASC), Senate Armed Service Committee (SASC), and House Appropriations Committee (HAC) must be notified by the service Secretary for approval (OPNAV INST 20H 2015).

Table 7: Operations and Maintenance (O&M) Budget: Sustainment, Restoration and Modernization (SRM) Special Interest Codes (SIC) (Adapted from CNIC 2016c)
Sustainment (ST)
Facilities sustainment is defined as the maintenance and repair activities necessary to keep a typical inventory of facilities in good working order. Sustainment includes regularly scheduled maintenance as well as cyclical major repairs or replacement of components that occur periodically over the expected service life of the facilities.
Restoration and Modernization (Recapitalization) (RM)
Recapitalization is defined as major renovation or reconstruction activities (including facility replacements) needed to keep existing facilities modern and relevant in an environment of changing standards and missions. Recapitalization extends the service life of facilities or restores lost service life. It includes restoration, modernization or replacement of facilities but not the acquisition of new facilities.
Facility New Footprint (NF)
New Footprint is defined as new construction work that addresses facility deficits. This may include either construction of new facilities or expansion of existing facilities. However, for projects where new construction work increases the size of an existing facility by less than 50 percent the work is categorized as modernization.
Demolition (DE)
Demolition is defined as dismantling and disposing of an excess real property facility either partially or in its entirety.
Combating Terrorism (CT)
Actions including antiterrorism (defensive measures taken to reduce vulnerability and property to terrorist acts, to include limited response and containment by local military forces) and counterterrorism (offensive measures taken to prevent, deter and respond to terrorism), taken to oppose terrorism throughout the entire threat spectrum.

The MEP is a great tool for local Public Works Departments since it is reviewed annually and then presented to the local FEC in order to obtain O&M funding for the fiscal year. Once funds are allocated to the Public Works Department, funds can be obligated to prioritized projects on the list. The MEP is internally reviewed typically on a month-to-month basis, and the list can be reprioritized as projects become more or less important due to other factors occurring at the installation level. The Public Works Officer has discretion to change priority and execute funding through the acquisition process, without seeking approval from higher leadership. Although this allows great freedom for local installations to react to facility or infrastructure concerns as necessary, if a high-visibility project that has been on a MEP previously reviewed and approved by FEC level leadership, and continues to be presented on future year budget requests, this may raise attention and inquiry of spending funding wisely and according to plan.

The MEP and O&M funding are an excellent tool for adaptation strategies that are smaller in value (less than $1 Million), for example adapting the envelope of facilities or utilities with dry flood proofing, installing flood gates, elevating equipment, or doing environmental restoration such as a wetland or a living shoreline. The concern is that O&M budgets are very tight year-to-year, and adaption strategies will have to compete with other ongoing maintenance and restoration needs. The MEP should be used as a tool to react to quickly emerging adaption concerns, and also as a tool that Public Works Staff uses f systematically year-to-year to adapt existing facilities and infrastructure that have long-service lives ahead of them. When the prioritization list of vulnerable infrastructure, facilities, or natural areas completed in step 5 of the evaluation framework is reviewed annually, it should be corresponding with the annual review of the MEP.

5.4 U.S. Navy Challenges of Placing Priority on Climate Change Adaptation

One of the challenging aspects of placing priority on climate change and related sea level rise is the contentious political atmosphere that surrounds anything referenced or is related to climate change. The military in general attempts to remain unbiased, and apolitical in nature while still moving forward with planning initiatives. The Navy specifically respects the unbiased approach to politics, but in the case of climate change and sea level rise is already feeling the impacts. In 2014 and in 2016, Republicans in the House of Representatives added language to Defense Department spending bills prohibiting funds from being spent to plan or prepare for climate change. Terrorism is the greater threat, the authors of those prohibitions declared, and federal funding should be steered towards snuffing out ISIS instead. Both times, the restrictions were nullified by the Senate (Parker 2017). In order, obtain funding from Congress the Navy must carefully approach the subject, while operationally they must be thinking assertively on climate change and how the Navy's mission as a whole will evolve over time, and how they can maintain operational readiness when installations are becoming increasingly vulnerable to the impacts of climate change and sea level rise.

One approach for operational readiness ashore is to not link climate change with sea level rise, and basically approach the two topics separately. As established in this thesis' literature review there is a plethora of research and studies on climate change, and specifically how the DOD and U.S. Navy views climate change. There is also hard-based science that demonstrates the sea level rise is occurring at multiple U.S. Navy installations around the country. As described in a recent article by National Geographic on *"Who's Still Fighting Climate Change? The U.S. Military"*- The Defense Department assiduously avoids the politics of climate science debate, while pressing ahead.

> *"We don't talk about climate change,"* In 2016 Capt. Dean VanderLey, NAVFAC Mid-Atlantic's Commanding Officer told visiting journalists touring Naval Station Norfolk, one of the most vulnerable naval installations in the United States to sea level rise. *"We talk about sea-level rise. You can measure it."* (Parker 2017).

By separating sea level rise and the associated coastal flooding from climate change, the Navy can link the science of historic sea level elevations, with current sea level heights, and documented flood events with mission readiness. The goal is to remove politics from the equation, and instead show a narrowed field of facts, and how sea level rise ashore is related to the Navy's ability to perform operationally within its mission set.

5.4.1 NAVFAC Placing a Priority on Resiliency

At the local level Public Works Department's feel the pain of sea level rise and infrastructure damage due to coastal flooding from a storm event or high tide. Although adaptation projects may be planned locally to increase resiliency on a project-by-project basis, large-scale U.S. Navy resiliency for shore infrastructure will not be achieved unless NAVFAC places a priority on sea level rise and associated coastal flooding.

As demonstrated by NAVFAC's aggressive policy for research, investment, and long-term planning for energy efficiency and green-energy implementation, NAVFAC could make significant strides in sea level rise adaptation if they did the following:

1. *Adaptation as a Priority*-NAVFAC Headquarters must include sea level rise adaptation as a strategic goal within its Strategic Plan. This demonstrates to subordinate commands that this is a priority, and that they are instructed and empowered to take the sea level rise seriously at an installation and regional FEC level.
2. *Publish Defined Goals*- The key success to the aggressive energy goals that NAVFAC achieved was that there was an established baseline year, and then targeted goals for implementation on a yearly basis over a decade. This decade long goal allowed enough time for real implementation, while also allowing for a long enough period of time to document the energy savings and how they were specifically linked to projects. This savings of energy, which translates into saving of money, was and continues to be an excellent tool for NAVFAC and ultimately the Navy to demonstrate to Congress that money was well invested.
3. *Publish Guidance*-As demonstrated with energy efficiency program, NAVFAC provided enough guidance on how they wanted to achieve energy efficiency (green infrastructure, public-private partnerships, and detailed design codes through the Unified Facilities Code) in

order to create a unified strategy across the Navy, while also allowing enough flexibility for individual installations to make energy decisions that best suit their installation needs.

4. *Encourage Innovation Sharing*- NAVFAC encouraged and still to this day, an atmosphere of innovation related to energy infrastructure. Continuous learning opportunities for engineers and architects was provided to stay on top of current energy trends. NAVFAC's Engineering and Expeditionary Warfare Center (EXWC) focuses on research, design, and implementation of new and pioneering energy infrastructure that is implement across naval installation arounds the world. A similar focus on new technology applications related to sea level rise would create an atmosphere of innovation, and would get the best and brightest planners, engineers, and architects within NAVFAC to explore opportunities to employ these technologies into their current and future projects. Fortunately, NAVFAC has established the Navy Climate Working Group to address climate change concerns. This group periodically conducts meetings for NAVFAC staff around the world to call in and hear the latest news on climate change initiatives, but at this time they are still in the infancy phase of exploring and implementing innovative adaptation strategies.
5. *Designate Specific Funding Streams*- NAVFAC working in coordination with CNIC has designated a certain portion of its O&M funding stream each year to projects designated as "energy projects". Local Public Works Departments could compete for energy project funding at the FEC level, and these funds would be above and beyond the typical O&M budget distributed at their local installation each fiscal year. By creating an opportunity for PW Leadership to plan and compete for adaptation projects, this enables PWO's to increase their overall budget and projects that can be completed each year, and encourages PW staff to link current infrastructure and facility deficiencies with sea level rise or coastal flooding projects. Bottom line, where money flows to in a budget, innovation and action will follow.

5.5 Transferability

This thesis was intended to create a consolidated planning and design evaluation framework that would empower military facilities engineers to make educated and confident decisions on what adaptation strategies best suit their specific installation risk and vulnerability to sea level rise. The *Adaptation Evaluation Framework for Sea Level Rise, Storm Surge, and Coastal Flooding* is not a complete prescriptive design or planning code or guidance, instead it is a tool that:

1. Identifies specific risk and vulnerability at a localized level to sea level rise, storm surge, and coastal flooding.
2. Empowers and fosters a planning and implementation team comprised of various stakeholders.
3. Enables facilities managers to make an educated decision on what design or planning strategy best fits their physical and operational requirements, so they then can move confidently forward detailed design.

As demonstrated in the literature review, there is an abundance of information available to study on risk analysis, and adaptation strategies. In reality though most planners and facility managers are incredibly busy with their day-to-day tasks, and do not have the time to research in detail and understand the plenitude of adaption options available. This evaluation framework enables decision makers to narrow down the best adaptation option, and once determined further research and planning can be focused into that one strategy more efficiently. Although the evaluation framework considers the operational requirements of the U.S. Navy, other public functional requirements could be substituted for military operations, and thus the framework is a valuable tool that could be employed by city planners and facility managers.

6. CONCLUSION

6.1 From Mitigation to Adaptation

The DOD and specifically the Navy have demonstrated strong mitigation practices for climate change through their innovative and aggressive energy programs. The second critical step in improving resiliency within our U.S. military installations, and ultimately national security is by taking these same top down strategies and applying them to climate change and specifically sea level rise adaptation. In relation to climate change, the DOD and its service departments can use their mitigation strategies and leadership approaches as related to energy policy, as a good example of how to approach climate change adaptation initiatives. Successful strategies include:

- Clearly defined policy, goals and initiatives that are written in official orders.
- Set quantifiable goals and targets, with repercussions if targets are not met.
- Strong buy-in from leadership up and down the chain, to interpret, empower, and hold those accountable for implementing policy.
- Accept and explore innovative and alternative technology. The military can serve as a leader in industry for new technology, and once proven help that technology transition into the public realm.
- Ensure funding is available for research, design and construction.
- Explore innovative contract types to fund major projects and partner with industry leaders.

6.2 Recommendations for Future Research

As discussed throughout this thesis climate change and sea level rise can be a political topic, which polarizes different stakeholders. One of the best strategies to demonstrate the toll climate change, and specifically sea level rise and associated coastal flooding has on military installations, is to perform an analysis of yearly damage to military installations due to flooding. Damage should be quantified in not only dollars terms, but also operational terms. Operations that must be suspended periodically due to equipment (ships, planes, and/or land vehicles) not being able to perform in flooded areas, or because staff cannot get to work in a timely fashion or perform their duties because of flooding, all have a direct impact to mission readiness. Quantifiable dollars spent to rebuild or clean up after flooding, productive man-hours lost to military/civilian personnel reacting/cleaning up after a flood event, as well as mission sets that are performing below targeted levels, all demonstrate to higher leadership that not adapting to sea level rise will have great continued costs. This research could also be applied to a city, port, or industrial complex to validate the requirement for adaptation.

Although this thesis discussed a spectrum of adaptation strategies, and their associated benefits, concerns, costs, maintenance requirements, and resiliency parameters, there are some strategies that have been employed less, and thus have less precedence to demonstrate their long-term performance. In depth research on the performance of ecosystem based strategies within traditional industrial complexes such as an active military installation would be beneficial to prove their worth, and understand the complexities of implementation. For example, case study research on living seawalls, living shorelines, and/or wetland restoration within a military/industrial complex needs further study. New and emerging technologies, such as the floating pier that is currently in the design and testing phase with the Navy is an innovative solution that could be applied to other forms of industrial infrastructure. With the cost of these piers being in the 100's of millions of dollars, a study on how they perform operationally and the amount of maintenance required to sustain them, will be a huge indicator to the Navy if they choose to apply this strategy for the replacement of all their vulnerable piers in the future.

6.3 Recommendations for Practitioners

Coastal facilities managers are intimately aware of the challenges of maintaining facilities and infrastructure along our coastlines, and sea level rise will only continue to exacerbate the costs and resources needed to preserve development. By first acknowledging the risk and vulnerabilities unique to the installation or city, coastal facilities managers can feel empowered to take action. With strained budgets for maintenance and new construction, adaptation should not be viewed as a one-strategy plan. Instead innovative coastal facility managers must look at systematic opportunities to increase resiliency by first siting new projects on land not vulnerable to flooding, second build in resiliency to new structures under development, and last logically adapt through maintenance or renovation the most vulnerable and critical existing infrastructure first.

The final goal of this thesis was to provide an evaluation framework that enables military coastal facilities managers to have confidence with assessing risk, vulnerability, and ultimately choosing with confidence an adaption strategy that best suits their unique needs. The detailed focus on understanding the benefits, concerns, costs, maintenance, and resiliency implications of each adaptation strategy was not to overwhelm the practioneer, but instead to empower them to make a logical and robust decision on an adaptation strategy, which will be further developed in the design development stages with a licensed architect or engineer. Lastly the *Protect, Accommodate, or Retreat: Spectrum of Adaptation Strategies* is intended to make coastal facilities managers think outside of the box, and investigate alternative strategies that they may not be accustomed to. Although sea walls and revetments have their definite merits on creating resiliency and a hard shoreline edge, other strategies that use the local ecosystem as a defense mechanism also have their merits and should be considered in a comprehensive installation or citywide adaptation plan.

7. BIBLIOGRAPHY

Abel, Gorddard, Harman, Leitch, Langridge, Ryan, and Heyenga. "Sea Level Rise, Coastal Development and Planned Retreat: Analytical Framework, Governance Principles and an Australian Case Study." Environmental Science and Policy 14, no. 3 (2011): 279-88.

Advisory Committee on the International Decade for Natural Hazard Reduction, 1989. Reducing Disasters' Toll: The United States Decade for Natural Disaster Reduction. Washington: National Academy Press.

American Society of Healthcare Engineers (ASHE). "Application of NFPA 99 in Health Care Facilities." Certified Health Care Manager, WRNMMC, Bethesda, MD, January 2015.http://www.ashe.org/education/nfpa99/index.shtml

ANMC21. "Asian Network of Major Cities 21." Asian Network of Major Cities 21 Best Practices. Accessed December 13, 2016. http://www.seisakukikaku.metro.tokyo.jp/gaimubu/anmc21/anmc21org/english/bestpractice/Tokyo5.html.

Barbier, Edward B., Evamaria W. Koch, Brian R. Silliman, Sally D. Hacker, Eric Wolanski, Jurgenne Primavera, Elise F. Granek, Stephen Polasky, Shankar Aswani, Lori A. Cramer, David M. Stoms, Chris J. Kennedy, David Bael, Carrie V. Kappel, Gerardo M. E. Perillo, and Denise J. Reed. "Coastal Ecosystem-Based Management with Nonlinear Ecological Functions and Values." Science319, no. 5861 (2008): 321-23.

Barbier, Edward B. et al. 2008. “Coastal Ecosystem-Based Management with Nonlinear Ecological Functions and Values,” in *Science.* Vol. 319. January 2008.

Barbut, Monique, 2014. Climate Change and Desertification a Threat to Social Stability - UN. April 17, 2014. Thomson Reuters Foundation. http://news.trust.org//item/20140416104118-jqc8k

Barnett, Jon. "Security and Climate Change." *Tyndall Centre Working Paper No. 7*, October 2001.

Bedford Carp Construction Inc. "Seawall Construction, Marine Construction NYC Governors Island." Seawall Construction, Marine Construction NYC Governors Island. Accessed December 13, 2016. http://bedfordcarp.com/projects/governors-island-seawall-rehabilitation/.

Bellingham Marine. "Floating Breakwater Attenuator Bellingham Marine." Floating Breakwater - Attenuator - Bellingham Marine. Accessed December 13, 2016. http://www.nauticexpo.com/prod/bellingham-marine/product-22401-95915.html.

Berger ABAM. "Floating Double-Deck Pier." Floating Double-Deck Pier | BergerABAM. Accessed December 13, 2016. http://www.abam.com/portfolio/project/164.

Berry, Ashton, Fahey, Shireen, and Meyers, Noel. "Changing of the Guard: Adaptation Options That Maintain Ecologically Resilient Sandy Beach Ecosystems." Journal of Coastal Research 29, no. 4 (2013): 899.

Bhatt, Uma S., Donald A. Walker, John E. Walsh, Eddy C. Carmack, Karen E. Frey, Walter N. Meier, Sue E. Moore, Frans-Jan W. Parmentier, Eric Post, Vladimir E. Romanovsky, and William R.

Simpson. "Implications of Arctic Sea Ice Decline for the Earth System." Annual Review of Environment and Resources 39 (2014): 57-89.

Bilkovic, D.M., and Mitchell, M.M. "Ecological Tradeoffs of Stabilized Salt Marshes as a Shoreline Protection Strategy: Effects of Artificial Structures on Macrobenthic Assemblages." Ecological Engineering 61 (2013): 469-81.

Brown, Lester R. *Full Planet, Empty Plates: The New Geopolitics of Food Scarcity*. Rutgers University: Earth Policy Institute, 2012.

Brown, Marilyn A., and Benjamin K. Sovacool, 2011. *Climate change and global energy security: technology and policy options*. Cambridge, The MIT Press. ISBN 978-0-262-51631-0

Browne M, Chapman MG. "Ecologically Informed Engineering Reduces Loss of Intertidal Biodiversity on Artificial Shorelines." Environmental Science and Technology 45(19) (2011) :8204–8207

Browne, Ma, and Mg Chapman. "Mitigating against the Loss of Species by Adding Artificial Intertidal Pools to Existing Seawalls." Marine Ecology Progress Series 497 (2014): 119-29. doi:10.3354/meps10596.

Bulleri F (2005) Experimental evaluation of early patterns of colonization of space on rocky shores and seawalls. Marine Environmental Research 60:355–374

Burby, Raymond J., and Linda C. Dalton. "Plans Can Matter! The Role of Land Use Plans and State Planning Mandates in Limiting the Development of Hazardous Areas." Public Administration Review 54, no. 3 (1994): 229-38. doi:10.2307/976725.

Busby, Joshua. "Climate Change and National Security: An Agenda for Action." *Council on Foreign Relations*, November 2007. CSR NO. 32.

Caldwell, Meg, and Holt Segall, Craig. "No Day at the Beach: Sea Level Rise, Ecosystem Loss, and Public Access Along the California Coast." Ecology Law Quarterly 34 (2007): 533-1349.

"Center for Coastal Resources Management." Living Shorelines. Accessed November 28, 2016. http://ccrm.vims.edu/livingshorelines/.

Chang, Biao, Jiabao Guan, and Mustafa M. Aral. "Scientific Discourse: Climate Change and Sea-Level Rise." Journal of Hydrologic Engineering 20, no. 1 (2015): A4014003.

Chapman M. "Paucity of mobile species on constructed seawalls: effects of urbanization on biodiversity." Marine Ecology Progress Series (2003) 264:21–29

Chapman, M.. "Intertidal Seawalls as Habitats for Molluscs." Journal of Molluscan Studies 72, no. 3 (2006): 247-57. doi:10.1093/mollus/eyi069.

Chapman, M, and Bulleri, F. "Intertidal seawalls—new features of landscape in intertidal environments." Landscape and Urban Planning (2003) 62:159–172

Charmaz, Kathy. Constructing Grounded Theory : A Practical Guide through Qualitative Analysis. London ; Thousand Oaks, Calif.: Sage Publications, 2006.

Chesapeake Bay Foundation. "Living Shorelines-For The Chesapeake Bay Watershed." September 2007. http://www.cbf.org/Document.Doc?id=60.

City of Seattle. "About the Project." Waterfront Seattle. Accessed December 13, 2016. http://www.waterfrontseattle.org/.

CMI. 2014. Vinyl Sheet Piling. Accessed December 13, 2016. http://cmisheetpiling.com/wp-content/uploads/2014/10/Vinyl-Sheet-Piling-Bulkhead.jpg

---.2014. Vinyl Marine Piling. Accessed December 13, 2016. http://cmisheetpiling.com/wp-content/uploads/2014/10/Vinyl-Marine-Bulkhead.jpg

Coastal News Today. "Netherlands – Dutch Turn Dikes into Innovative Sites to Fight Floods." Netherlands – Dutch Turn Dikes into Innovative Sites to Fight Floods | Coastal Engineering News & Subscription List. Accessed December 13, 2016. http://coastalnewstoday.com/netherlands-dutch-turn-dikes-into-innovative-sites-to-fight-floods/.

Commander Navy Installations Command (CNIC). 2016a. "Reducing Shore Energy Costs." Reducing Shore Energy Costs. Accessed October 12, 2016. http://www.cnic.navy.mil/om/base_support/facility_system_investment/Navy_Shore_Energy_Program.html.

---..2016b. "Naval Station Norfolk." Naval Station Norfolk. Accessed December 13, 2016. http://www.cnic.navy.mil/regions/cnrma/installations/ns_norfolk.html.

---..2016c. “SRM Branch”. Accessed February 8, 2017. https://www.cnic.navy.mil/om/base_support/facility_system_investment/srm_branch.html

Coumou, Dim, and Stefan Rahmstorf. "A Decade of Weather Extremes." Nature Climate Change, 2012. doi:10.1038/nclimate1452.

County of Santa Clara (SCC). "Floodplain Ordinance." Floodplain Ordinance - Planning and Development - County of Santa Clara. Accessed December 13, 2016. https://www.sccgov.org/sites/dpd/PlansOrdinances/FloodPlain/Pages/FloodPlain.aspx.

Crooks, S., D. Herr, J. Tamelander, D. Laffoley, and J. Vandever. 2011. “Mitigating Climate Change through Restoration and Management of Coastal Wetlands and Near-shore Marine Ecosystems: Challenges and Opportunities.” Environment Department Paper 121, World Bank, Washington, DC.

Davis JL, Currin CA, O’Brien C, Raffenburg C, Davis A (2015) Living Shorelines: Coastal Resilience with a Blue Carbon Benefit. PLoS ONE 10(11): e0142595. doi:10.1371/journal.pone.0142595

DE URBANISTEN. "River Dike Rotterdam." DE URBANISTEN. Accessed December 13, 2016. http://www.urbanisten.nl/wp/?portfolio=rivierdijk-rotterdam.

Dean, R.G. and Dalrymple, R.A. 2002. Coastal Processes with Engineering Applications. Cambridge: Cambridge University Press.

Dehghani, A.a., H.md. Azamathulla, S.a. Hashemi Najafi, and S.a. Ayyoubzadeh. "Local Scouring around L-head Groynes." Journal of Hydrology 504 (2013): 125-31. doi:10.1016/j.jhydrol.2013.09.020.

Department of Defense (DOD). 2008. DoD 7000.14 – R. *Financial Management Regulations.* Department of Defense. http://comptroller.defense.gov/Portals/45/documents/fmr/Volume_02a.pdf

---.2010. *Quadrennial Defense Review Report.* Department of Defense. *http://www.defense.gov/qdr/images/QDR_as_of_12Feb10_1000.pdf*

---.2011. Energy, Environment, Safety & Occupational Health Network and Information Exchange. "FY 2011 Secretary of Defense Environmental Award Natural Resources Conservation - Team 1 NAVAL SUPPORT ACTIVITY PANAMA." News release, 2011. Accessed November 28, 2016. http://www.denix.osd.mil/awards/fy11secdef/nrcit/naval-support-activity-panama-city-environmental-staff-fl/.

---.2014a. *2014 Climate Change Adaptation Roadmap*. Department of Defense. http://www.acq.osd.mil/ie/download/CCARprint_wForeword_c.pdf

---.2014b. *Department of Defense Annual Energy Management Report Fiscal Year 2013*. Office of the Deputy Under Secretary of Defense (Installations and Environment). http://www.acq.osd.mil/ie/energy/energymgmt_report/FY%202013%20AEMR.pdf

---.2016a. Climate Change Adaptation and Resilience. *DOD DIRECTIVE 4715.2*. http://www.dtic.mil/whs/directives/corres/pdf/471521p.pdf

---.2016b. Regionalized Sea Level Change & Extreme Water Level Scenarios-User Guide V2.0. https://www.serdp-estcp.org/News-and-Events/News-Announcements/Program-News/DoD-Report-on-Regional-Sea-Level-Scenarios

---.2016c. Department of Defense (DoD) Releases Fiscal Year 2017 President's Budget Proposal. Feb 9, 2016. http://www.defense.gov/News/News-Releases/News-Release-View/Article/652687/department-of-defense-dod-releases-fiscal-year-2017-presidents-budget-proposal

---.2016d. Office of the Assistant Secretary of Defense for Energy, Installations, and Environment. "About Us." http://www.acq.osd.mil/eie/AboutUs.html

Department of Homeland Security (DHS). Department of Energy. Energy Sector-Specific Plan: An Annex to the National Infrastructure Protection Plan 2010.

Department of Navy (DON). 2010. "Navy Climate Change Road Map". http://www.navy.mil/navydata/documents/CCR.pdf

---.2012. Strategy for Renewable Energy. October 2012. www.secnav.navy.mil/eie/Documents/DoNStrategyforRenewableEnergy.pdf

---.2014. OPNAV INSTRUCTION 11010.20H. Navy Facilities Projects. May 16, 2014. https://doni.daps.dla.mil/Directives/11000%20Facilities%20and%20Land%20Management%20Ashore/11-00%20Facilities%20and%20Activities%20Ashore%20Support/11010.20H%20-%20CH-1.PDF

---.2016. "Mission of the Navy." Navy Organization. Accessed October 12, 2016. http://www.navy.mil/navydata/organization/org-top.asp

Dickson, Eric, Judy L. Baker, Daniel Hoornweg, and Asmita Tiwari. Urban Risk Assessments: An Approach for Understanding Disaster and Climate Risk in Cities. Washington, D.C.: World Bank, 2012.

Dowall, David E., and Whittington, Jan. Making Room for the Future : Rebuilding California's Infrastructure. San Francisco, Calif.: Public Policy Institute of California, 2003.

Dronkers, J., Gilbert, J. T. E., Butler, L.W., Carey, J.J., Campbell, J., James, E., McKenzie, C., Misdorp, R., Quin, N., Ries, K.L., Schroder, P.C., Spradley, J.R., Titus, J.G., Vallianos, L., and von Dadelszen. J. 1990. Coastal Zone Management. In CLIMATE CHANGE: THE IPCC RESPONSE STRATEGIES. Geneva: Intergovernmental Panel on Climate Change.

Duarte, C.M., Middelburg, J.J., Caraco, N. (2005) Major Role of Marine Vegetation on the Oceanic Carbon Cycle. Biogeosciences 2:1–8.

Dugan, Jenifer E., David M. Hubbard, Iván F. Rodil, David L. Revell, and Stephen Schroeter. "Ecological Effects of Coastal Armoring on Sandy Beaches." Marine Ecology 29 (2008): 160-70.

Dyson, Karen, and Ken Yocom. "Ecological Design for Urban Waterfronts." *Urban Ecosystems Urban Ecosyst* 18, no. 1 (2014): 189-208. doi:10.1007/s11252-014-0385-9.

EBA Engineering Consultants Ltd. Marine Compensation Habitat Survey Report Vancouver Convention Centre West. Technical Report prepared for B.C. Pavilion Corporation (PAVCO). (2011). EBA File: V23201073.

Environmental Protection Agency (EPA). Guiding Principles for Constructed Treatment Wetlands: Providing for Water Quality and Wildlife Habitat. Washington, D.C., Washington: United States Environmental Protection Agency, Office of Water, 2000. https://nepis.epa.gov/Exe/ZyPDF.cgi/2000536S.PDF?Dockey=2000536S.PDF

---2016a. "Why Are Wetlands Important?" EPA. Accessed November 28, 2016. https://www.epa.gov/wetlands/why-are-wetlands-important.

---2016b. "Coastal Wetlands." EPA. Accessed November 30, 2016. https://www.epa.gov/wetlands/coastal-wetlands.

---2016c. "Climate Impacts on Energy." Accessed December 08, 2016. https://www.epa.gov/climate-impacts/climate-impacts-energy.

---2017. "Urban Runoff: Low Impact Development." Accessed March 9, 2017 https://www.epa.gov/nps/urban-runoff-low-impact-development

ESCP. "Eastern Solent Coastal Partnership." Beach Nourishment | Eastern Solent Coastal Partnership. Accessed December 13, 2016. http://www.escp.org.uk/beach-nourishment.

Farber, Stephen. "The Value of Coastal Wetlands for Protection of Property against Hurricane Wind Damage." *Journal of Environmental Economics and Management* 14, no. 2 (1987): 143-51.

Federal Emergency Management Agency (FEMA). FEMA 102, Floodproofing for Non-Residential Structures. Washington, D.C.,1986. https://www.fema.gov/media-library/assets/documents/15599.

---1999. Protecting Building Utilities From Flood Damage. Washington, D.C., 1999. https://www.fema.gov/pdf/fima/pbuffd_complete_book.pdf

---2007. FEMA 551, Selecting Appropriate Mitigation Measures for Floodprone Structures. Washington, D.C., 2007. https://www.fema.gov/media-library-data/20130726-1609-20490-5083/fema_551.pdf

---2008. Free-of-Obstruction Requirements- for Buildings Located in Coastal High Hazard Areas in accordance with the National Flood Insurance Program. Washington, D.C., 2008. https://www.fema.gov/media-library-data/20130726-1511-20490-9526/fema_tb_5.pdf

---2012. FEMA P-259, Engineering Principles and Practices of Retrofitting Floodprone Residential Structures, Third Edition (2012). Washington, D.C., 2012. https://www.fema.gov/media-library/assets/documents/3001

---2013. Reducing Flood Effects in Critical Facilities. Washington, D.C., 2013.

---2016a. "Building Codes." Building Codes | FEMA.gov. Accessed December 05, 2016. https://www.fema.gov/building-codes.

---2016b. “Coastal High Hazard Area” | FEMA.gov. Accessed December 05, 2016. https://www.fema.gov/building-codes.

---2016c. “Zone V” | FEMA.gov. Accessed December 05, 2016. https://www.fema.gov/building-codes

---2016d. “Flood Zones” | FEMA.gov. Accessed December 05, 2016. https://www.fema.gov/flood-zones

Fidelity Engineering Corporation. 2013. “High Performance Building Solutions." Fidelity Engineering Corporation. Accessed December 08, 2016. http://fidelityengineering.com/wp-content/uploads/2013/04/finished-sg2-rooftop.jpg

Firth L, Thompson R, White F, Schofield M, Skov M, Hoggart S, Jackson J, Knights A, Hawkins S. 2013. The importance of water-retaining features for biodiversity on artificial intertidal coastal defence structures. Diversity and Distributions. doi:10.1111/ddi.12079

Fletcher C.H., Mullane R.A., Richmond B.M. (1997) Beach loss along armored shorelines on Oahu, Hawaiian Islands. Journal of Coastal Research, 13(1), 209–215.

Flood Control America. "FLOOD PROOFING PROJECT - BOTHELL, WA." Flood Walls - Bothell | Removable Flood Walls - Flood Control America. Accessed December 08, 2016. http://floodcontrolam.com/projects/flood-wall-bothell/.

Francis, Robert A., and Jamie Lorimer. "Urban Reconciliation Ecology: The Potential of Living Roofs and Walls." Journal of Environmental Management 92, no. 6 (2011): 1429-437. doi:10.1016/j.jenvman.2011.01.012.

Freesteel Blog. " North Wales Bike Coast." Freesteel Blog RSS. Accessed December 13, 2016. http://www.freesteel.co.uk/wpblog/goatchurch-org-uk/north-wales-bike-coast/.

French, P.W. 2001. Coastal defenses: Processes, Problems, and Solutions. London: Routledge.

Gacia E, Paola M, Martin D. 2007. Low crested coastal defence structures on the Catalan coast of the Mediterranean Sea: how they compare with natural rocky shores. Scientia Marina 71(2):259–267

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. & Tempio, G. 2013. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome

Gittman, Rachel K., Alyssa M. Popowich, John F. Bruno, and Charles H. Peterson. "Marshes with and without Sills Protect Estuarine Shorelines from Erosion Better than Bulkheads during a Category 1 Hurricane." Ocean & Coastal Management 102 (2014): 94-102. doi:10.1016/j.ocecoaman.2014.09.016.

Goff, M. 2008. Effect of Habitat Enhancement on Urban Seawall Ecology. Technical report, University of Washington, School of Aquatic and Fishery Sciences: Wetland Ecosystem Team.

Goff, M. 2010. Evaluating Habitat Enhancements of an Urban Intertidal Seawall: Ecological Responses and Management Implications. Master Thesis. School of Aquatic and Fishery Sciences, University of Washington.

Griggs G.B. 2005a. California's retreating coastline: where do we go from here? In: Magoon O.T., Converse H., Baird B., Miller-Henson M. (Eds), California and the World Ocean, Conference '02 Revisiting and Revising California's Ocean Agenda. American Society of Civil Engineers, Preston, VA: 121–125.

Griggs G.B. 2005b. The impacts of coastal armoring. Shore and Beach, 73(1), 13–22.

Hall M.J., Pilkey O.H. 1991. Effects of hard stabilization on dry beach widths for New Jersey. Journal of Coastal Research, 7(3), 771–785.

Hall, J.A., S. Gill, J. Obeysekera, W. Sweet, K. Knuuti, and J. Marburger. 2016. *Regional sea level scenarios for coastal risk management: Managing the uncertainty of future sea level change and extreme water levels for Department of Defense coastal sites worldwide.* Washington, DC: U.S. Department of Defense, Strategic Environmental Research and Development Program. Online at *https://www.serdp-estcp.org/News-and-Events/News- Announcements/Program-News/DoD-Report-on-Regional-Sea- Level-Scenarios,* accessed Oct 20, 2016.

Hanak, Ellen, and Georgina Moreno. "California Coastal Management with a Changing Climate." Climatic Change 111, no. 1 (2012): 45-73.

Harris, Marc, Robert Dixon, Nicholas Mellin, Daniel Hendrex, Richard Russo, and Michael Bailey. "Megacities and the United States Army, Preparing For a Complex and Uncertain Future." Chief of Staff of the Army, Strategic Studies Group, June 2014, 1-28.11.

HDR Inc. "Corpus Christi Seawall." Corpus Christi Seawall. Accessed December 13, 2016. http://www.hdrinc.com/portfolio/corpus-christi-seawall.

Hinrichsen, Don. "THE COASTAL POPULATION EXPLOSION." National Oceanic and Atmospheric Administration (NOAA). 1999. http://oceanservice.noaa.gov/websites/retiredsites/natdia_pdf/3hinrichsen.pdf.

Irfan, Umair. "ADAPTATION: New $1.1B Sea Wall Protects New Orleans against Major Storms but May Cultivate Complacency." May 15, 2014. E&E Publishing. Accessed November 09, 2016. http://www.eenews.net/stories/1059999621.

IPCC. 2014. Summary for Policymakers. In: Climate Change 2014: Synthesis Report. Aldunce, Paulina, Thomas Downing, Sylvie Joussaume, Zbigniew Kundzewicz, Jean Palutikof, Jim Skea, Kanako Tanaka, Fredolin Tangang, Chen Wenying, Zhang Xiao-Ye, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jansen, M. 1990. The role of coastal zone management in sea level rise response. In Changing Climate and the Coast: Report of the Intergovernmental Panel on Climate Change from the Miami Conference on Adaptive Responses to Sea Level Rise and Other Impacts of Global Climate Change. Geneva, Switzerland: United Nations Environment Program, 1990.

Jebb, Parrigon, and Woo. "Exploratory Data Analysis as a Foundation of Inductive Research." Human Resource Management Review 27, no. 2 (2017): 265-76.

Johns Hopkins Medicine. "Portfolio." Johns Hopkins Bayview Medical Center, ASC Generator Building | Henry Adams Consulting Engineers. Accessed December 08, 2016. http://www.henryadams.com/portfolio/infrastructure-healthcare/johns-hopkins-bayview-medical-center-asc-generator-building.

Kamphuis, J.W. "Introduction to Coastal Management." Advanced Series on Ocean Engineering Introduction to Coastal Engineering and Management, 2000, 227-56. doi:10.1142/9789812386403_0010.

Kriesel W, and Friedman R. “Coping with coastal erosion: evidence for community-wide impacts.” ShoreBeach 71 (2003):19–23

Kong, D, Setunge, S, Molyneaux, T, Zhang, G & Law, D 2013, *Structural resilience of core port infrastructure in a changing climate.* Work Package 3 of Enhancing the resilience of seaports to a changing climate report series, National Climate Change Adaptation Research Facility, Gold Coast, 172 pp.

Langridge, Suzanne M., Hartge, Eric H., Clark, Ross, Arkema, Katie, Verutes, Gregory M., Prahler, Erin E., Stoner-Duncan, Sarah, Revell, David L., Caldwell, Margaret R., Guerry, Anne D., Ruckelshaus, Mary, Abeles, Adina, Coburn, Chris, and O'Connor, Kevin. "Key Lessons for Incorporating Natural Infrastructure into Regional Climate Adaptation Planning."*Ocean and Coastal Management* 95 (2014): 189-97.

Lanier, Michael W., Markus Wernli, Robert Easley, and Preston S. Springston. "New Technologies Proven in Precast Concrete Modular Floating Pier for U.S. Navy." PCI Journal 50, no. 4 (2005): 76-99. doi:10.15554/pcij.07012005.76.99.

Lindell, Michael K., Carla S. Prater, and Ronald W. Perry. *Fundamentals of Emergency Management*. 2006. http://training.fema.gov/hiedu/aemrc/booksdownload/fem/.

Linham, Matthew, and Robert Nicholls. "Technology Info: Seawalls." ClimateTechWiki. Accessed November 9, 2016. http://www.climatetechwiki.org/content/seawalls#Advantages of the technology.

Lochmueller Group. "Constructed Wetlands, Construction Inspection, Featured Project." Lochmueller Group. Accessed December 13, 2016. http://lochgroup.com/project/constructed-wetlands-for-cso-treatment/.

Long, Charles, and Stephenson. "Key Principles of Marine Ecosystem-based Management." Marine Policy 57 (2015): 53-60.

Lucky, R. W., and Jon Eisenberg. Renewing U.S. Telecommunications Research. Washington, D.C.: National Academies Press, 2006. https://www.nap.edu/catalog/11711/renewing-us-telecommunications-research

Lukens, R. and C. Selberg, editors. 2004. Guidelines for Marine Artificial Reef Materials (Second ed.). Artificial Reef Subcommittes of the Atlantic and Gulf States Marine Fisheries Commissions.

Marlowe, Justin, William C. Rivenbark, and A. John. Vogt. *Capital budgeting and finance: a guide for local governments*. Washington, D.C.: ICMA Press, 2009.

McGraw Building Media (MBM). "Smart Vents." McGraw Building Media Continuing Education. Septemeber 2012. Accessed December 13, 2016. http://mcgrawimages.buildingmedia.com/CE/CE_images/2016/March-Design-for-Extreme-Enviroments-8.jpg.

---.2016. "Design for Extreme Environments." McGraw Building Media Continuing Education. March 2016. Accessed December 13, 2016. http://mcgrawimages.buildingmedia.com/CE/CE_images/2016/March-Design-for-Extreme-Enviroments-8.jpg.

McGregor, Alisdair, Cole Roberts, and Fiona Cousins. Two Degrees: The Built Environment and Our Changing Climate. Abingdon, Oxon: Routledge, 2013.

Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, Eds. 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program. doi:10.7930/J0Z31WJ2.

Morgan, Pamela A., David M. Burdick, and Frederick T. Short. "The Functions and Values of Fringing Salt Marshes in Northern New England, USA." Estuaries and Coasts 32, no. 3 (2009): 483-95. doi:10.1007/s12237-009-9145-0.

Morse, J., Stern, P., Corbin, J., Bowers, B., Charmaz, K., & Clark, A. (2009). Developing Grounded Theory: The Second Generation. Walnut Creek, CA: Left Coast Press.

National Academies Press. Committee on National Security Implications of Climate Change for U.S. Naval Forces, Naval Studies Board, Division on Engineering and Physical Sciences, and National Research Council. National Security Implications of Climate Change for U.S. Naval Forces. National Academies Press, 2011.

National Academy of Sciences (NAS). 2011. *National security implications of climate change for U.S. naval forces: A report by the Committee on National Security Implications of Climate Change for U.S. Naval Forces.* Washington, DC. Online at *https://www.nap.edu/download/12914*, accessed Oct 20, 2016.

National Air and Space Association (NASA). "Global Warming." Earth Observatory. Accessed October 19, 2016. http://earthobservatory.nasa.gov/Features/GlobalWarming/.

National Fire Protection Association (NFPA). NFPA 99: Health Care Facilities Code, 2012. Washington, D.C., 2012

---.NFPA 101: Life Safety Code, 2015. Washington, D.C., 2015

National Oceanic and Atmospheric Administration (NOAA). 2015a. "Living Shorelines" US Department of Commerce, National Oceanic and Atmospheric Administration. 2015.Accessed December 12, 2016. http://www.noaanews.noaa.gov/stories2015/121615-noaa-study-finds-living-shorelines-can-lessen-climate-changes-effects.html

---.2015b. "Habitat Blue Print" US Department of Commerce, National Oceanic and Atmospheric Administration. 2015.Accessed December 12, 2016. https://www.habitatblueprint.noaa.gov/living-shorelines/

---.2016. "What Percentage of the American Population Lives near the Coast?" US Department of Commerce, National Oceanic and Atmospheric Administration. Accessed December 12, 2016. http://oceanservice.noaa.gov/facts/population.html.

National Research Council . Committee on Sea Level Rise in California, Oregon, Washington. Sea-level Rise for the Coasts of California, Oregon, and Washington : Past, Present, and Future. Washington, D.C.: National Academies Press, 2012.

Naval Facilities Engineering Command (NAVFAC).2013. TDS-NAVFAC EXWC-CI-1410 "Floating Double-Deck Pier". DEC 2013. http://www.navfac.navy.mil/content/dam/navfac/Specialty%20Centers/Engineering%20and%20Expeditionary%20Warfare%20Center/PDFs/ci_tech_data_sheets/TDS-NAVFAC-EXWC-CI-1410.pdf

---.2016. "Strategic Design". http://www.navfac.navy.mil/about_us/navfac-strategic-design-2016-2019.html

North Carolina Coastal Federation. "Terminal Groins | North Carolina Coastal Federation.". Accessed December 13, 2016. http://www.nccoast.org/protect-the-coast/advocate/terminal-groins/.

NYC Department of Planning. 2013a. "COASTAL CLIMATE RESILIENCE Urban Waterfront Adaptive Strategies". New York City Planning, Sustainable Communities. June 2013. http://www1.nyc.gov/site/planning/plans/sustainable-communities/climate-resilience.page?tab=2.

---.2013b. "A Stronger More Resilient New York." New York City Planning, Office of Recovery and Resiliency. June 2013. http://s-media.nyc.gov/agencies/sirr/SIRR_singles_Lo_res.pdf

New York City Economic Development Commission (NYCEDC). "Rising to the Challenge: FW Brown and Flood Panel." NYCEDC. July 28, 2015. Accessed December 13, 2016. http://www.nycedc.com/blog-entry/rising-challenge-fw-brown-and-flood-panel.

O'Brien, Paul. "Groynes - for What Purpose? - Coastal Engineering Solutions." Coastal Engineering Solutions. April 7, 2014. Accessed November 10, 2016. http://www.coastengsol.com.au/groynes-for-what-purpose/.

O'Connor, Tim. "Seattle Department of Transportation – Elliott Bay Seawall Project." Construction Today. 2016. Accessed November 09, 2016. http://www.construction-today.com/sections/civil/2204-seattle-department-of-transportation-elliott-bay-seawall-project

Oktay, Julianne S. Grounded Theory. Pocket Guides to Social Work Research Methods. Oxford ; New York: Oxford University Press, 2012.

Ostrowski, R., Pruszak, Z., Schönhofer, J., & Szmytkiewicz, M. (2016). Groins and submerged breakwaters - new modeling and empirical experience.*Oceanological and Hydrobiological Studies*, *45*(1), 20-34. doi:http://dx.doi.org.offcampus.lib.washington.edu/10.1515/ohs-2016-0003

PA Times. "Sustainable Coastal Restoration and Stabilization: Living Shoreline Project on Florida's East Coast." PA TIMES Online. 2014. Accessed December 13, 2016. http://patimes.org/sustainable-coastal-restoration-stabilization-living-shoreline-project-floridas-east-coast/.

Panoramio. "Panama 2013, Colon, Long Breakwater." Panoramio - Photo of Panama 2013, Colon, Long Breakwater, Kristina Cruises Tours View. 2013. Accessed December 13, 2016. http://www.panoramio.com/photo/85492505.

Parker, Laura. "Who's Still Fighting Climate Change? The U.S. Military." National Geographic. February 7, 2017. Accessed February 8, 2017. http://news.nationalgeographic.com/2017/02/pentagon-fights-climate-change-sea-level-rise-defense-department-military/.

Parris, A., P. Bromirksi, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. Weiss. 2012. *Global Sea Level Rise Scenarios for the US National Climate Assessment*. NOAA Tech Memo OAR CPO-1.

Paulina, Thomas Downing, Sylvie Joussaume, Zbigniew Kundzewicz, Jean Palutikof, Jim Skea, Kanako Tanaka, Fredolin Tangang, Chen Wenying, Zhang Xiao-Ye, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Piers Blaikie, Terry Cannon, Ian Davis, and Ben Wisner. (2004). *At risk: Natural hazards, people's vulnerability and disasters, 2nd ed.* London: Routledge.

Pietrafesa, L.j. "On the Continued Cost of Upkeep Related to Groins and Jetties." Journal of Coastal Research 284 (2012): Iii-Ix. doi:10.2112/jcoastres-d-12a-00004.1.

Pinto, Francisco T. and Neves, Ana Cristina Valente. "Environmental Aspects of Using Detached Breakwaters for Coastal Protection Purposes." *Management of Environmental Quality: An International Journal* 15, no. 1 (2004): 62-71.

Professional Media Management (PMM). "GIS." March 3, 2015. Accessed December 13, 2016. http://i0.wp.com/professionalmediamanagement.com/wp-content/uploads/2015/03/GIS.jpg.

Rosenzweig, Cynthia, William D. Solecki, Stephen A. Hammer and Shagun Mehrotra. 2011. *Climate change and cities: first assessment report of the Urban Climate Change Research Network*. Cambridge, UK: Cambridge University Press

RRM Design Group. "Surfer's Point Managed Shoreline Retreat and Trail." RRM Design Group - Engineering & Surveying - Surfer's Point Managed Shoreline Retreat and Trail. 2004.

Samaras, Constantine. ‘U.S. Military Basing Considerations during a Rebalance to Asia: Maintaining Capabilities under Climate Change Impact’, in ‘The US Asia-Pacific Rebalance, National Security and Climate Change’, The Center for Climate and Security, 2015.

S.B. Ballard. "Va Beach Seawall | S.B. Ballard." Accessed November 9, 2016. http://www.sbballard.com/portfolio/va-beach-seawall/.

Sciortino, J. A. Fishing Harbour Planning, Construction and Management. Rome: Food and Agriculture Organization of the United Nations, 2010. http://www.fao.org/docrep/013/i1883e/i1883e00.htm

Scott, Esther. *Hurricane Katrina (A): Preparing for "The Big One" in New Orleans*. Report. Kennedy School of Government, Harvard University. C15-06-1843.0. Cambridge, MA: Case Program, 2006.

Slogan, J. Marine community dynamics on engineered fish compensation habitat in Burrard Inlet, BC. Presentation at the 2011 Salish Sea Ecosystem Conference, Wednesday October 26th, 2011 in Vancouver, Canada. Online: http://www.verney.ca/ssec2011/presentations_d2.php

Strategic Environmental Research and Development Program (SERDP). 2016. “Tools and Training.”. https://www.serdp-estcp.org/Tools-and-Training

Sheng, Y. Peter, Andrew Lapetina, and Gangfeng Ma. "The Reduction of Storm Surge by Vegetation Canopies: Three-dimensional Simulations." *Geophysical Research Letters* 39, no. 20 (2012): N/a.

Sims Municipal Recycling (SIMS). "State-of-the-Art Material Recovery Facility in Sunset Park, Brooklyn." Sunset Park Material Recovery Facility | Curbside Recycling | New York City Curbside Recycling | Sims Metal Management | Sims Municipal Recycling. Accessed December 02, 2016. http://www.simsmunicipal.com/NYC/Sunset-Park-MRF.

SNH. "A Guide to Managing Coastal Erosion in Beach/dune Systems." A Guide to Managing Coastal Erosion in Beach/dune Systems. Accessed December 13, 2016. http://www.snh.org.uk/publications/on-line/heritagemanagement/erosion/appendix_1.14.shtml.

Spencer, Jack. "The Facts About Military Readiness." The Heritage Foundation. September 15, 2000. Accessed December 14, 2016. http://www.heritage.org/research/reports/2000/09/bg1394-the-facts-about-military-readiness.

Strategic Environmental Research and Development Program (SERDP), ‘Assessing Impacts of Climate Change on Coastal Military Installations: Policy Implications’, US Department of Defense, 2013.

Syvitski JP, Vörösmarty CJ, Kettner AJ, Green P. 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308(5720):376–380

Tanks Direct. "Preventing Flotation of Underground Storage Tanks | Tanks Direct." Tanks Direct. 2015. Accessed December 08, 2016. http://www.tanksdirect.com/blog/preventing-flotation-underground-storage-tanks/.

Terchunian, Aram V. "Permitting Coastal Armoring Structures: Can Seawalls and Beaches Coexist?" *Journal of Coastal Research*, 1988, 65-75.

The World Bank. Turn down the Heat: Why a 4°C Warmer World Must Be Avoided. Report. Washington, DC: World Bank, 2012.

---2013. Building Resilience: Integrating climate and disaster risk into development. Lessons from World Bank Group experience. The World Bank, Washington DC.

Tripati, A. K., C. D. Roberts, and R. A. Eagle. "Coupling of CO2 and Ice Sheet Stability Over Major Climate Transitions of the Last 20 Million Years." Science 326, no. 5958 (2009): 1394-397. doi:10.1126/science.1178296.

Trenberth, Ken. "Changes in Precipitation with Climate Change." Climate Research 47, no. 1 (2011): 123-38. doi:10.3354/cr00953.

United Nations (UN). “Framework Convention on Climate Change”. Technical Paper. May 25, 1999. http://unfccc.int/resource/docs/tp/tp0199.pdf

---.2016. "Sustainable Development Knowledge Platform." Accessed October 19, 2016. http://sustainabledevelopment.un.org/natlinfo/indicators/methodology_sheets/oceans_seas_coasts/pop_coastal_areas.pdf.

United States Army Corp of Engineers (USACE). 2016a. "PORTLAND DISTRICT." Mouth of the Columbia River Jetties. Accessed November 10, 2016. http://www.nwp.usace.army.mil/Missions/Current/Columbia-River-jetties/.

---.2016b. "NORFOLK DISTRICT." Norfolk District About Projects TangierJetty. Accessed November 10, 2016. http://www.nao.usace.army.mil/About/Projects/TangierJetty.aspx

United States Congress. "H.Amdt.1195 to H.R.5293 - 114th Congress (2015-2016)." H.Amdt.1195 to H.R.5293 - 114th Congress (2015-2016) | Congress.gov | Library of Congress. Accessed December 12, 2016. https://www.congress.gov/amendment/114th-congress/house-amendment/1195.

United States Fish & Wildlife. "U.S. Fish & Wildlife Service Proposed Dual Jetty System at Oregon Inlet on North Carolina’s Outer Banks" Accessed November 10, 2016. https://www.fws.gov/nc-es/oregon/Oregon_Inlet_Fact_Sheet.pdf.

Walker, Brian, C. S. Holling, Stephen R. Carpenter, and Ann P. Kinzig. "Resilience, Adaptability and Transformability in Social-ecological Systems." *Ecology and Society* 9, no. 2 (2004). doi:10.5751/es-00650-090205.

Washington State Department of Ecology. 2016a. "Puget Sound Shorelines: Building - Bulkheads." Puget Sound Shorelines: Building - Bulkheads. Accessed December 1, 2016. http://www.ecy.wa.gov/programs/sea/pugetsound/building/bulkhead.html.

---.2016b. "Wetland Stewardship Resources and Grant Programs | National Coastal Wetlands Conservation Grant Program | Washington State Department of Ecology." Wetland Stewardship Resources and Grant Programs | National Coastl Wetlands Conservation Grant Program | Washington State Department of Ecology. Accessed December 13, 2016. http://www.ecy.wa.gov/programs/sea/wetlands/stewardship/nwcgp.html.

Wamsley, Cialone, Smith, Atkinson, and Rosati. "The Potential of Wetlands in Reducing Storm Surge." *Ocean Engineering* 37, no. 1 (2010): 59-68.

Weber, Mark. "What Is the Difference Between a Seawall and a Bulkhead?" MW Engineering INC. June 29, 2014. http://mwengineering.net/what-is-the-difference-between-a-seawall-and-a-bulkhead/.

Weebly."Groins / Jetty." The Agents of Erosion. Accessed December 13, 2016. http://erosionagents4shapingearth.weebly.com/groins--jetty.html.

Williams J, Dellapenna T, Lee G. 2013. Shifts in depositional environments as a natural response to anthropogenic alterations: Nakdong Estuary, South Korea. Marine Geology 343:47–61

Wilson, Marcel. "ESP // Estuary Services Pipeline." | News | Archinect. April 7, 2012. Accessed December 14, 2016. http://archinect.com/news/article/45335738/bracket-goes-soft-esp-estuary-services-pipeline.

Woods Hole Group. 2011 "Beach Nourishment in Progress on Martha’s Vineyard." 2Fathom. 2011. Accessed December 13, 2016. https://woodsholegroup.wordpress.com/2011/01/14/beach-nourishment-in-progress-on-marthas-vineyard/.

APPENDIX

A. Interview List

The individuals below were consulted during the research of this thesis. All of these individuals serve in some form of leadership within NAVFAC, and either oversee planning, maintenance, or construction on coastal naval installations. They were consulted to discuss current practice related to planning and adaptation for sea level rise, not for opinions related to climate change or sea level rise science.

Individuals Consulted for Current NAVFAC Adaptation Policies		
Name	Organization	Title
Robin O'Connell	DON-NAVFAC	Director, Sustainability & Land Use Planning Senior Climate Change Advisor Asset Management (AM3), NAVFAC HQ
CAPT Matt Anderson, PE	DON-NAVFAC	Executive Officer/Deputy Regional Engineer NAVFAC Northwest
CDR Roland Deguzman, PE	DON-NAVFAC	Director Integrated Product Team Hampton Roads NAVFAC Mid-Atlantic
LCDR Riley Smith, PE	DON-NAVFAC	Director, Facilities Engineering and Acquisition Division NAVFAC Washington Public Works Department Annapolis
LT Corinne Sims, PE	DON-NAVFAC	NAVFAC Atlantic
Brian Crowder, PE	DON-NAVFAC	Deputy Business Director Business Planning and Review NAVFAC Mid-Atlantic