Storm Surge & Critical Infrastructure on Nantucket

by
Brian Bach
Cecelia Cotter
Matthew Lepine
Sean Regan

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by
Brian Bach
Cecelia Cotter
Matthew Lepine
Sean Regan

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Report Submitted to:

Dave Fronzuto
Nantucket Emergency Management Agency

Peter Morrison
Demographer, Project Liaison

Professors Dominic Golding and Reinhold Ludwig
Worcester Polytechnic Institute

Abstract

Storm surge, produced by increasingly frequent severe storms, threatens the daily operations of downtown Nantucket. This project identifies and analyzes ways the Town might protect Nantucket's downtown critical infrastructure from storm surge and offers recommendations for mitigating future adverse impacts. In collaboration with Dave Fronzuto and the Nantucket Emergency Management Agency, we assessed the risks caused by storm surge for each piece of infrastructure within the downtown area and developed a prioritized list of infrastructure to be modified. We compiled a database of relevant information for each infrastructure element in our study area, along with a GIS layer to facilitate data retrieval.

Acknowledgements

We thank our two project sponsors, Emergency Management Coordinator **Dave Fronzuto**, and Demographer **Peter Morrison**. Dave Fronzuto furnished a wealth of detailed information on Nantucket's bouts with storm surge in the past. Peter Morrison offered helpful insights on approaching different aspects of the issues posed by storm surge. Both offered ongoing project guidance and suggestions for acquiring the information and tools that enabled us to reach our goal. We also thank our project advisors, **Dominic Golding** & **Reinhold Ludwig**, for their guidance and oversight in developing and executing this project.

In addition, we thank the following individuals for assisting us in completing our project:

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- **Frank Holdgate**, Surveyor, for surveying critical pieces of infrastructure, and teaching us how to calculate the base floor elevations. We want to give a special thanks to Frank for going out of his way, on his own time, to help us gather information.
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Dave Fronzuto providing insights into base floor elevation.

Executive Summary

High winds and excessive precipitation cause tremendous damage in severe storms, but "the greatest threat to life comes from the water in the form of storm surge" (Hurricane Storm Surge), as it has the potential to severely damage critical infrastructure and fatally disrupt the lives of nearby inhabitants in coastal areas. Storm surge is best defined as the "abnormal rise in water level, over and above the regular astronomical tide, caused by a severe storm" (Storm Surge and Coastal Inundation). Projections of future sea level indicate that ocean levels will likely rise, intensifying the associated problems.

Nantucket's tourist-based economy and ever growing population heightens the need for action. "There are two primary reasons for the dramatic increase in natural disaster-related losses: an increase in the people and property in harm's way, and an increase in the frequency or severity of the hazard events" (U.S. Army Corps of Engineers, Water Resources Science, Engineering, and Planning: Coastal Risk Reduction; Water Science and Technology Board; Ocean Studies Board; Division on Earth and Life Studies; National Research Council, 2014). These two primary factors call for actions to be taken to mitigate the threats of potential natural disaster-related losses looming in Nantucket's future.

In particular, it is important that the Town embark on a long-range effort to protect its most critical pieces of infrastructure, which pose the greatest threat to the community's viability if damaged. Damage to a community's critical infrastructure threatens the public health, environment, and economy.

This project identifies and evaluates potential ways to protect Nantucket's critical downtown infrastructure from storm surge and offers recommendations for mitigating future adverse impacts. Our project had four main objectives:

1. Evaluate past and current practices, along with recognized best practices, for protecting critical infrastructure to determine what approaches have proven to be most successful;
2. Identify and characterize critical infrastructure in the defined downtown study area;
3. Evaluate the advantages and disadvantages of alternative planning, protective, and mitigation strategies for different infrastructural elements; and
4. Formulate and prioritize and recommendations for the future.

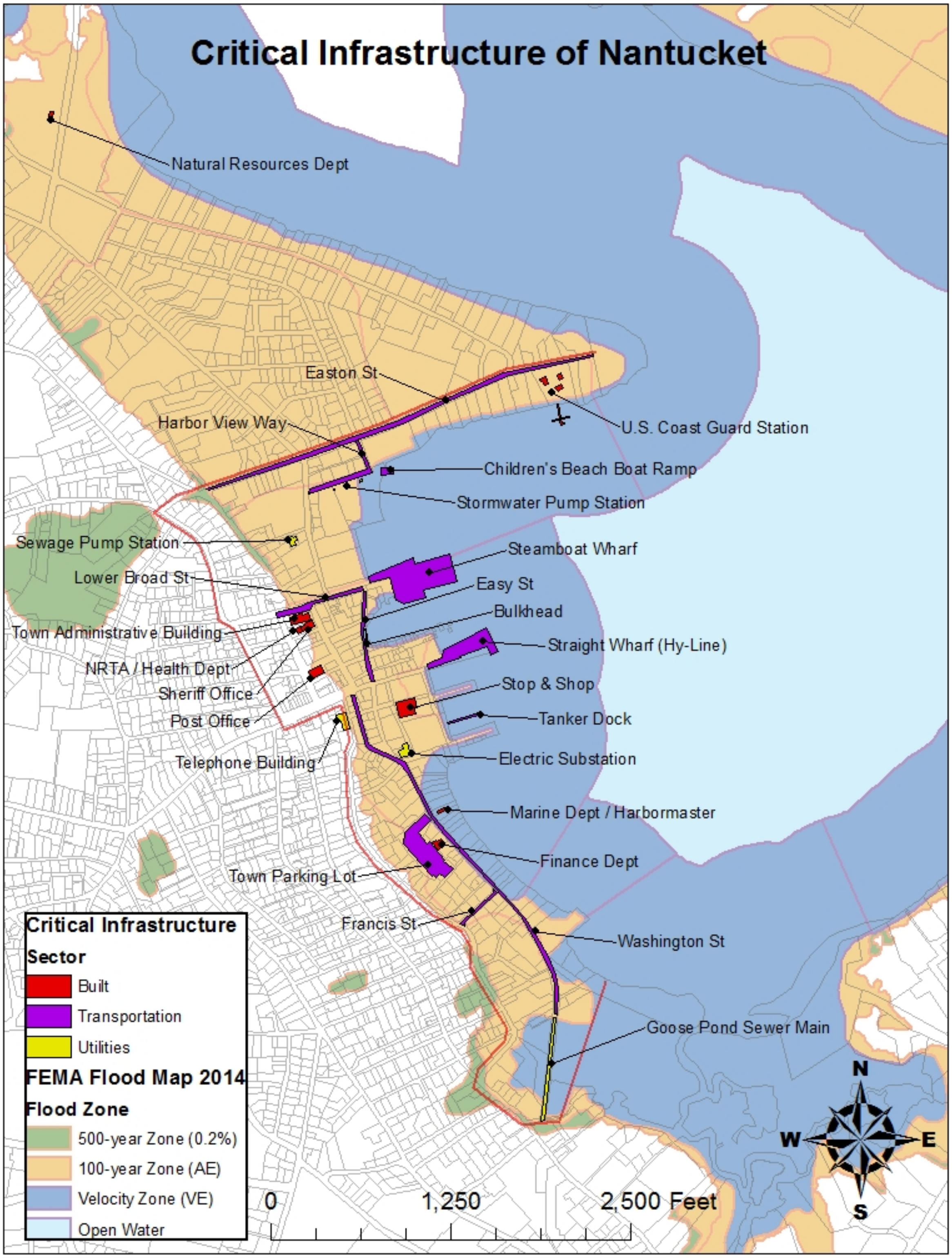
We began by reviewing the research on these topics to understand storm surge and its effects on communities, and protection measures that have been used in the past. To better understand the specific Nantucket context, we interviewed several knowledgeable local experts to gain an understanding of how the problems associated with storm surge are presently dealt with on the Island.

To identify and characterize critical Town infrastructure, we first defined our study area based on FEMA flood maps. FEMA has defined several types of "zones," including the 100-year flood, or base flood, zone that shows those areas that face a one-percent annual risk of flooding equal to or exceeding a defined height (the so-called "once in a century" height). We used this area as a baseline for defining the boundary of downtown infrastructure that falls within the 100-year flood zone lower than 10 feet above sea level. Based on further discussions with the Emergency Management Coordinator, Dave Fronzuto, we defined our area of interest. Next, we focused on identifying elements of critical infrastructure essential to the day-to-day operations of the Town and its residents situated within that area of interest.

Our next step entailed developing data-gathering checklists referencing three categories of infrastructure: utilities, built, and transportation. We used this typology as a guide when collecting data in the field, drawing upon findings from the literature review and information from consultations with our sponsors, advisors, and other experts noted previously. Key data we acquired for each piece of infrastructure includes the base floor elevation, which is the height that often determines when water can enter a building and begin to do interior damage, and the height of critical components, such as electrical connections.

Drawing upon these data, we performed a risk assessment for each individual piece of infrastructure. This assessment weighed the measured likelihood of damage by a 100-year storm surge versus the resulting consequences were that infrastructure to be rendered inoperable. Our assessment identified 7 high-risk, 11 medium-risk, 6 low-risk, and 2 very low-risk elements of infrastructure within our study area.

Based on our research, we identified three main ways to protect critical infrastructure: floodproofing, elevation, and relocation. For each piece of infrastructure, we have highlighted which of these three options is most effective. Elevation proves to be the most effective option for much of the infrastructure in our area of interest.


Critical Infrastructure of Nantucket
Natural Resources Dept
Easton St
U.S. Coast Guard Station
Harbor View Way
Children's Beach Boat Ramp
Stormwater Pump Station
Sewage Pump Station
Steamboat Wharf
Lower Broad St
Easy St
Bulkhead
Town Administrative Building
Straight Wharf (Hy-Line)
NRTA / Health Dept
Sheriff Office
Stop & Shop
Post Office
Tanker Dock
Telephone Building
Electric Substation
Marine Dept / Harbormaster
Finance Dept
Town Parking Lot
Francis St
Washington St
Goose Pond Sewer Main
Critical Infrastructure
Sector
Built
Transportation
Utilities
FEMA Flood Map 2014
Flood Zone
500-year Zone (0.2%)
100-year Zone (AE)
Velocity Zone (VE)
Open Water
0
1,250
2,500 Feet
N
W
E
S

Non-Relocatable Infrastructure: Elevate	Relocatable Infrastructure: Elevate
• Candle Street Substation • Children's Beach Stormwater Pump Station • Easy Street Bulkhead • Sea Street Pump Station • Steamboat Wharf • Straight Wharf (Hy-Line) • Tanker Dock	• Marine Department / Harbormaster's Office • Natural Resources Department • Sheriff's Office • U.S. Coast Guard Station
Non-Relocatable Infrastructure: Floodproof • Post Office • Stop & Shop	**Relocation of Function** • Finance Department • Town Administrative Building
No Further Action • Children's Beach Boat Ramp • Goose Pond Sewer Main • NRTA / Health Department • Union Street Telephone Building • Town Parking Lot	**Roads** • Easton Street • Easy Street • Francis Street • Harbor View Way • Lower Broad Street • Washington Street

We have prioritized all identified pieces of infrastructure according to which are most crucial for immediate repair, based on both the degree of risk and how critical the infrastructure is. Of particular note, both the Sea Street Pump Station and the Candle Street Substation are each at high risk and merit top priority for future work. Any proposed mitigation tactics have the potential to take several years to complete, so it is imperative that all aspects of the Town's planning take this into consideration.

To facilitate data retrieval in the future, we prepared a reference database, which we have made available in both digital and printed binder formats. This database furnishes the checklists, summaries, risk assessment, and recommendations for each individual element of critical infrastructure. Additionally, we have created a complementary Geographic Information System (GIS) database of pertinent infrastructure information, including its name, sector, value, ground elevation, critical elevation, risk value, and FEMA flood zone, along with the page number referencing the further information available in the database. The GIS layer incorporates currently existing layers used by Nantucket GIS, for seamless incorporation as a useful tool.

Authorship

Section	Author(s)	Editor(s)
Abstract	CC, ML	BB, ML
Executive Summary	BB, CC	BB, CC, ML, SR
Introduction	BB, CC, ML, SR	BB, CC, ML, SR
Background		
Storm Surge	ML	BB, CC, ML
Effects of Storm Surge	CC	BB, ML
Remediation of Storm Surge	BB, SR	ML
Nantucket	CC, SR	BB, CC, ML, SR
Methodology		
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Objective 2	BB, CC, ML, SR	ML
Objective 3	SR	ML
Objective 4	BB	ML
Findings		
Database of Infrastructure	BB, CC, ML, SR	BB, CC, ML, SR
Infrastructure Checklists	BB, CC	BB, CC, ML, SR
Summary & Ranking of Infrastructure	BB, CC, ML, SR	BB, CC, ML, SR
Conclusions and Recommendations		
Conclusions	CC	BB, ML
Recommendations	BB	ML
Recommended for Mitigation Tactics	CC, SR	ML
Other Recommendations	BB, CC	ML
Future Work	BB, CC	ML
Deliverables	CC, SR	BB, ML

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I • Introduction

Hurricanes, tropical storms, and nor'easters are among the greatest natural threats to the New England region. The Great New England Hurricane of 1938 made landfall on Long Island, NY with 100-mph winds and a 40-foot storm surge, killing 600 people and generating the equivalent of $18 billion in damages (The Great New England Hurricane). High winds and excessive precipitation cause tremendous damage in such storms, but "the greatest threat to life comes from the water in the form of storm surge" (Hurricane Storm Surge), which can severely damage critical infrastructure and fatally disrupt the lives of nearby inhabitants in coastal areas.

Because of global climate change, Nantucket can anticipate more frequent intense storms and two- to six-foot higher sea levels by 2100 in the vicinity of Boston (Climate change in New England, 2015). Storm surge will likely pose a severe and growing threat to New England's coastal and island communities like Nantucket. The Federal Emergency Management Agency (FEMA) has recently updated flood maps, causing great concern among many Nantucket residents and prompting attention to protecting homes and safeguarding Island infrastructure. Some residents are even building moats around electrical equipment and attaching hot water heaters to the basement ceiling of the their homes in efforts to minimize potential storm damage (Turer, 2015).

Damage to residential properties is but one concern. Storm surge can also wreak havoc on fundamental Town infrastructure—utilities providing electric power and emergency communication, roads affording access or escape in the face of emergency, and harbor facilities which are Nantucket's lifeline to the mainland and, ultimately, its source of most goods consumed on a daily basis. Residents and businesses depend on the continued functioning of this critical infrastructure, much of which happens to be situated near the downtown area waterfront.

Nantucket endeavors to improve its emergency planning and preparedness in various ways. For example, it is one of only twelve Massachusetts communities that have been certified by the National Weather Service as StormReady. In addition, the Town completed its Coastal Management Plan in 2014 and is now in the process of mapping storm tide pathways, thanks to a grant from the Massachusetts Coastal Community Planning Program. Nevertheless, the Town has not systematically examined the current condition of its critical infrastructure at risk due to storm surge.

Our project addresses this gap. It equips the Town with the necessary basis for deciding on future courses of action and prioritizing those actions given available resources. Our specific goal was to identify how the Town might protect critical infrastructure from storm surge. We conducted a systematic inventory and assessment of current conditions and vulnerability of critical infrastructure at risk of damage due to storm surge within the 100-year flood zone of downtown Nantucket. We have identified certain actions that Nantucket can take to protect various infrastructural elements, such as floodproofing, elevating, and relocating particular items of infrastructure. Furthermore, we have then recommended viable mitigation tactics whereby the Town can effectively protect both its inhabitants and its infrastructure from the recurring and pernicious damages caused by storm surge.

2 • Background

In this chapter, we review the devastating damage that storms have produced in recent history along the northeastern coast of the United States and distill lessons to be learned from those events. We begin by considering the scientific basis for anticipating more frequent intense storms and higher sea levels by 2100, due to the effects of climate change. We then examine the nature of storm surge and its effects on people and infrastructure in coastal areas. Finally, we review promising strategies for enhancing resilience and mitigating damages in coastal communities.

2.0.1 • Storms, Damage, & Climate Change

Storms and storm surge cause an immense amount of damage on the East Coast of the United States. Such damage is likely to increase in the future due to climate change and the increasing concentration of population and urban infrastructure in coastal zones. Hurricane Bob, which made landfall in Massachusetts in 1991, inflicted about $39 million in damages and produced a storm surge that reached up to 15 feet above the mean sea level ("The Worst Massachusetts Hurricanes of the 20th Century," 2015). Twenty years later, in the wake of Hurricane Irene, the state suffered $194.5 million in damages and encountered 786,000 power outages (The Associated Press, 2012).

"There are two primary reasons for the dramatic increase in natural disaster-related losses: an increase in the people and property in harm's way, and an increase in the frequency or severity of the hazard events" (U.S. Army Corps of Engineers, Water Resources Science, Engineering, and Planning: Coastal Risk Reduction; Water Science and Technology Board; Ocean Studies Board; Division on Earth and Life Studies; National Research Council 2014, p.12). This produces an increasingly dangerous situation; from 2000 to 2012, coastal communities grew by 11.4% throughout the entire East and Gulf Coasts, which contributed to the severity of damages from storms (U.S. Army Corps of Engineers, et al., 2014).

Storms have the potential to damage infrastructure through wind, precipitation, and ocean flooding. In coastal areas, hurricanes and tropical storms are among the most common threats that cause this damage. From 1900 to 2005, hurricanes and tropical storms were responsible for producing over $1 trillion in damage nationwide (Pielke, R., Gratz, J., Landsea, C., Collins, D., Saunders, M., & Musulin, R., 2008). Even winter storms are responsible for large-scale losses; from

2005 to 2014, $25 billion worth of damage and 760 fatalities occurred due to winter storms alone (Winter Storms, 2015).

Over the past 30 years, severe storms have struck the East Coast with increasing frequency. Figure 1 shows average costs associated with coastal storm events in the United States between 1980 and 2013, in 5-year increments (U.S. Army Corps of Engineers, et al., 2014). As you can see, the number of events and the costs associated with these events are increasing.

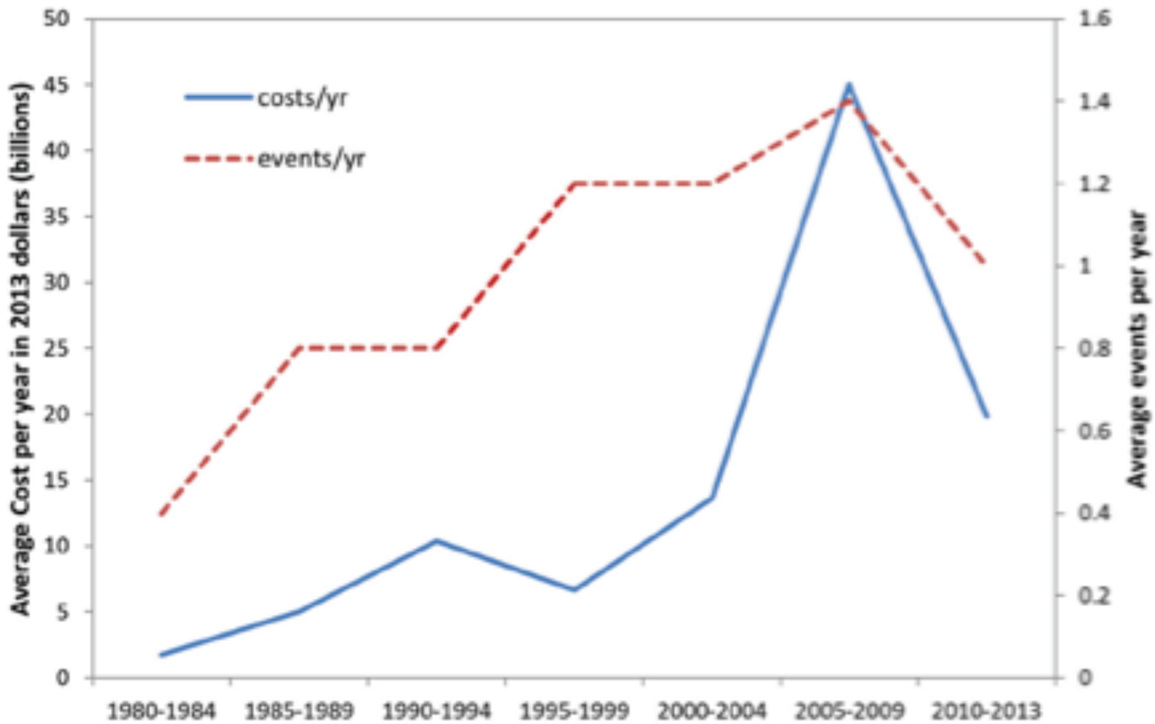

Figure 1: Average Annual Cost of Coastal Storms in the United States

Adapted from U.S. Army Corps of Engineers, Water Resources Science, Engineering, and Planning: Coastal Risk Reduction; Water Science and Technology Board; Ocean Studies Board; Division on Earth and Life Studies; National Research Council.

Climate change is likely to enhance the intensity and frequency of storms. "Management challenges are becoming more acute as current climate conditions appear to be producing more frequent, high intensity storms accompanied by large storm surges, resulting in more significant coastal storm, tide, and flooding events" (Fronzuto, 2014). Since 1970, the ocean temperature off of the coast of Southern New England has increased by 2.2 degrees Fahrenheit, causing a rise in sea level due to the thermal expansion of the seawater. Melting of polar ice caps has been releasing large volumes of water into the oceans, further contributing to sea level rise (Berman, G., & Simpson, J., 2014).

Two different projections for sea level rise are displayed in Figure 2, from a study done by researchers from Tufts University and the University of Massachusetts (Kirshen, P., Watson, C., Douglas, E., Gontz, A., Lee, J., & Tian, Y. 2007).

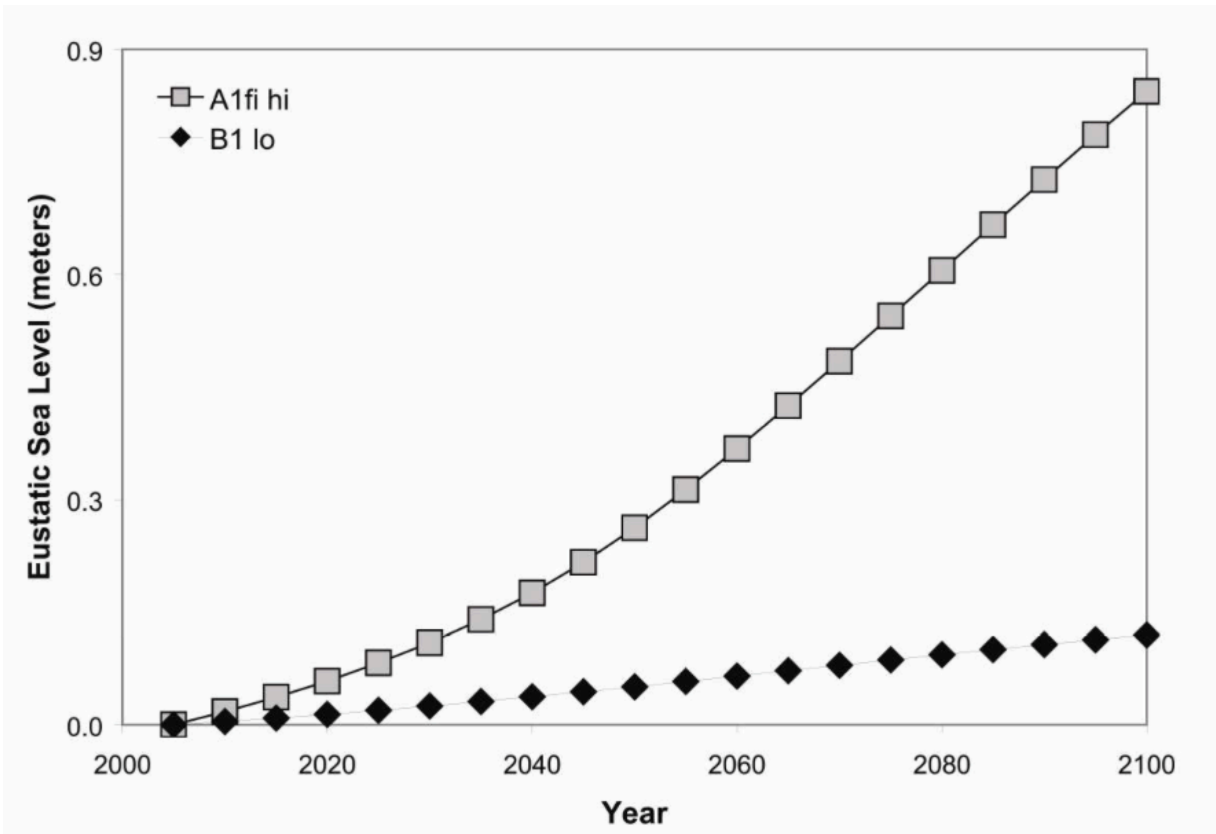

Figure 2: Sea Level Predictions - A1fi hi & B1lo

The B1lo projection was created under a lower greenhouse gas emission scenario while the A1fi hi projection was made with a stronger consideration for the oceans absorbing more heat and ice sheets melting faster.

Adapted from *Coastal flooding in the Northeastern United States due to climate change.*

Increases in sea level will bring about more damage to infrastructure. When applying the two projections, "Boston, Massachusetts, appears particularly susceptible to relative sea level rise (SLR) changes. Under both emission scenarios, by 2050 the 100-year storm surge will exceed the elevation of the 2005 1,000-year storm surge, and the recurrence interval of the 2005 100-year storm surge will be less than 15 years" (Kirshen, et al., 2007). These projections suggest a substantial threat, as more than 5,790 square miles of the United States' coastline and more than $1 trillion of property and structures are at risk of inundation from a sea level rise of two feet above current sea level (Davidson, Kirshen, Moser, Mulvaney, Murley, Neumann, Petes, and Reed, 2014). Exacerbating this issue, coastal populations are projected to grow from the current 46.2 million people to 131.2 million people by the year 2100, thus increasing the number of citizens potentially affected by the effects of global climate change (Davidson et al., 2014).

2.1 • Storm Surge

Storm surge is defined as the "abnormal rise in water level, over and above the regular astronomical tide, caused by a severe storm" (Storm Surge and Coastal Inundation). The average severe storm surge level is approximately 10 feet above the normal tide level (Storm Surge and Coastal Inundation). Some of the most destructive storms, however, can produce a surge of 30 feet or more. These severe storms, which can be hurricanes, tropical storms, nor'easters, or even blizzards, produce a storm surge that combines with the astronomical tide to establish the storm tide, as depicted in Figure 3.

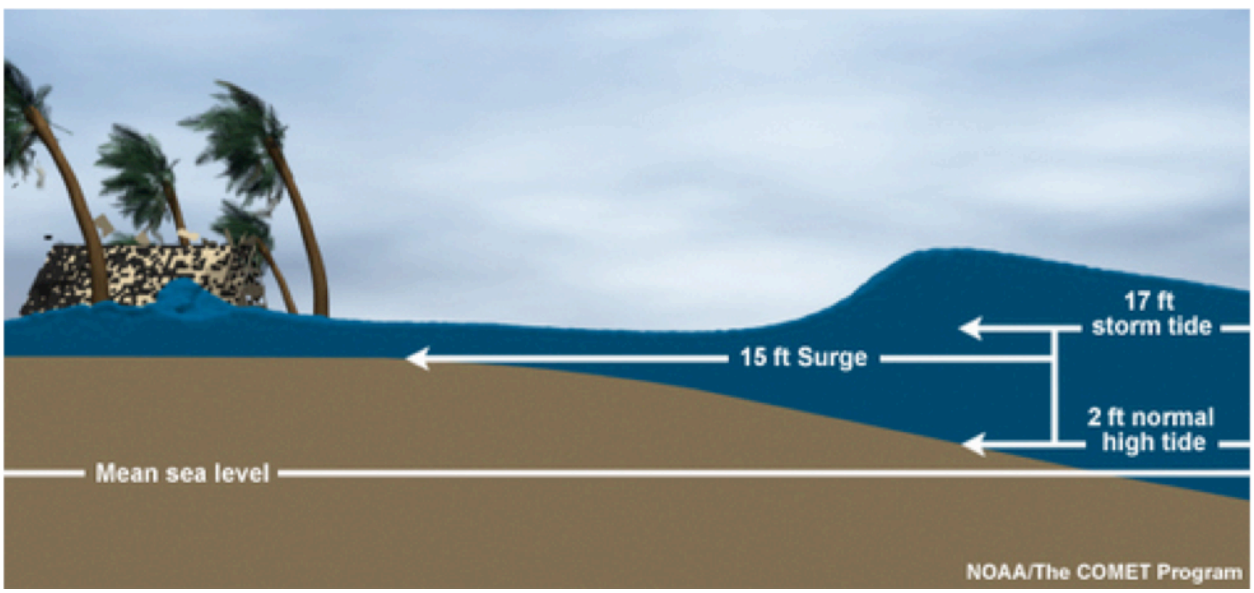

Figure 3: Storm Surge vs. Storm Tide

Adapted from http://www.nhc.noaa.gov/surge/

There are two types of surge: pressure surge and wind-driven surge (Figure 4). Pressure surge is normally formed in the eye of a storm, where the pressure is lowest, but its effect on the overall storm surge is modest. Wind-driven surge, however, is caused mainly by the strong winds from a storm. The wind from a storm generates a vertical circulation in the ocean. When the storm reaches shallower waters, the vertical circulation becomes disrupted, travels inward with the storm, and advances inland (Introduction to Storm Surge).

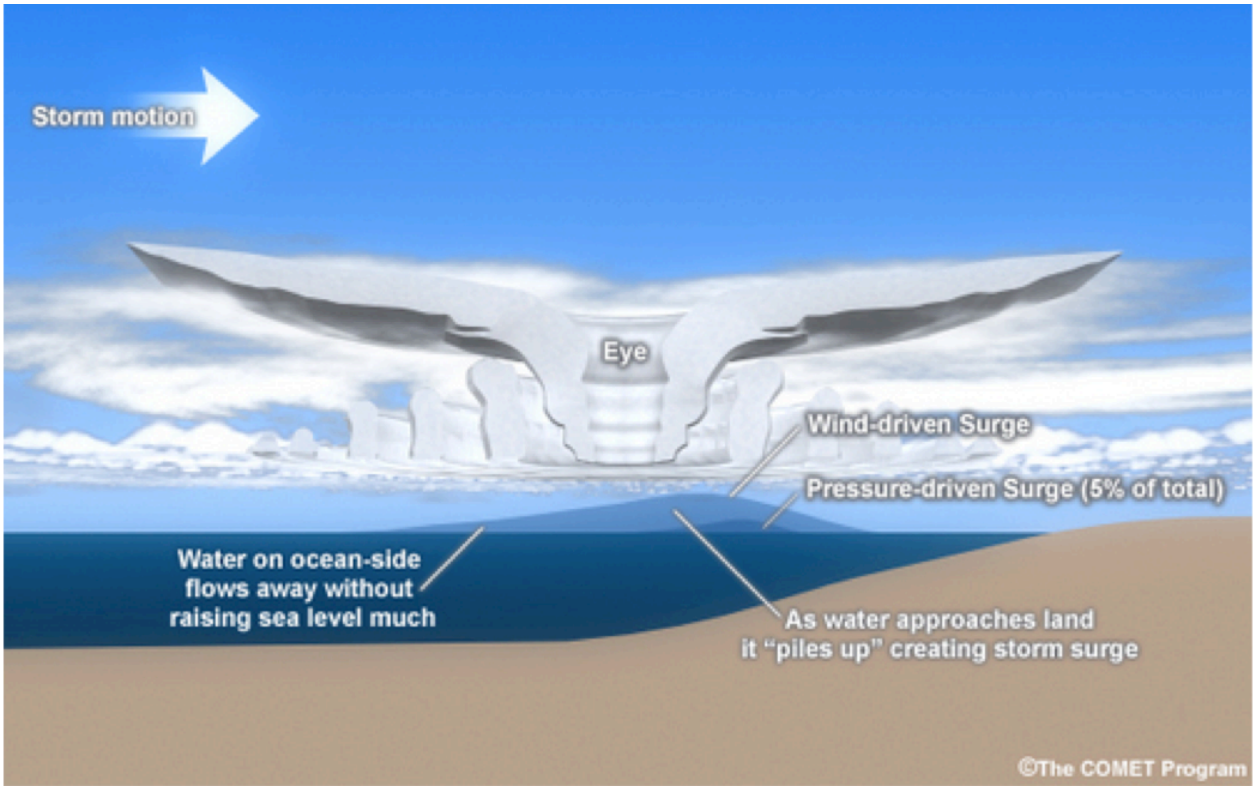

Figure 4: Wind and Pressure Components of Hurricane Storm Surge

Adapted from http://www.nhc.noaa.gov/surge/

Several elements affect storm surge, some more so than others. Lower pressures and stronger winds produce a larger storm surge, with the wind having a greater effect than the pressure on the intensity of the surge. A storm's physical size also has a powerful effect on the height of storm surge, not only because of the stronger winds, but also because of the greater area covered by larger storms. Additionally, a storm's speed has a substantial impact: a faster storm will generate a higher surge on a coast that is open to the ocean, whereas a slower storm will produce a higher surge for a coast that is bounded. The angle at which the storm approaches the coast will further impact the severity of the storm surge; if the storm travels directly toward the coast, it will have a greater impact than if the storm moves parallel to the coast (Introduction to Storm Surge).

Even the shape of the coastline can affect the storm surge; concave coastlines will typically experience a higher surge than convex coastlines. The topography of the ocean floor near the shore also determines the resultant storm surge; the surge is higher with a gently sloping ocean floor, as opposed to a steeply sloping ocean floor (Figure 5). Finally, various other local features can affect the intensity of the storm surge. For downtown Nantucket, jetties and other natural barriers are examples of features that can protect land from direct impact from the open ocean (Introduction to Storm Surge).

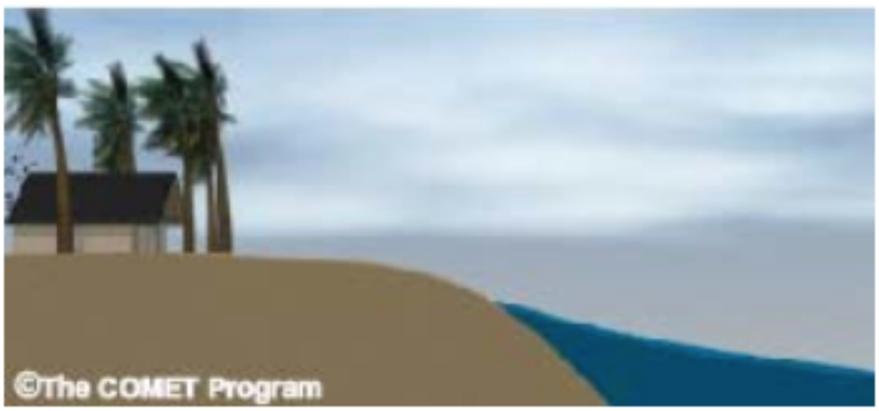

Figure 5: The Effect of the Ocean Floor on Storm Surge

(Top): Example of a gently sloping ocean floor. (Bottom): Example of a steeply sloping ocean floor.

Adapted from http://www.nws.noaa.gov/om/hurricane/resources/surge_intro.pdf

2.1.1 • Factors Contributing to the Total Water Level

Storm surge is only one component of water level rise during a storm. Among other factors are tides, waves, and freshwater input. Astronomical tides are affected by the gravitational pull of the sun and of the moon, and exist whether or not a storm is present. Waves also contribute to the overall water level through so-called runup and setup. Wave runup occurs when a wave breaks and shoots water up the beach. Wave setup arises when the water from the wave runup accrues on the coastline because the water cannot drain back out to the sea. Wave setup is especially critical, as it can affect coastal areas up to a few days before the storm, as the ocean becomes more agitated. Rainfall is yet another factor that can affect water levels; the rain adds onto the existing flooding, and may actually be the cause of flooding in some areas, especially around rivers or in bays where the rivers drain. All of these ingredients—storm surge, tides, waves, and rainfall—contribute to the total water level, which can wreak havoc on coastal communities before, during, and after a storm (Introduction to Storm Surge).

The total water level is a major concern when it comes to the effects of major storms. While storm surge is the major contributor to the overall water level in a storm, other factors—tides, waves, and rainfall—also affect the total level of inundation and the extent of flooding inland. The amount of water that is encompassed in the total water depth not only affects the extent of the inundated area—and thus the scope of the post-storm restoration area—but also the degree of vertical damage for various structures, which determines the protective measures that might be necessary.

2.2 • Effects of Storm Surge

Both the Federal Emergency Management Agency (FEMA) and the USA PATRIOT Act define critical infrastructure as "those assets, systems, networks, and functions—physical or virtual—so vital that their incapacitation or destruction would have a debilitating impact on security, national economic security, public health or safety, or any combination of those matters" (Critical Infrastructure and Key Resources Support Annex, 2008). Based on this national definition of critical infrastructure, we have formulated a local definition of critical infrastructure to be any type of infrastructure that is essential to the day-to-day operations of a town or city and its residents.

Local critical infrastructure, the only type of critical infrastructure we shall examine, falls into three sectors of infrastructure: utilities, built, and transportation (Table 1). If, for example, roads or bridges become blocked or destroyed due to storm surge, people could be trapped in an area out of reach of emergency services, including emergency medical services, fire fighting, and other responders, with potentially fatal consequences.

Table 1: Infrastructure & Factors Affecting Vulnerability

Sector	Infrastructure	Factors
Built Infrastructure	Private Buildings	Foundation Material, Floodproofing, Base Floor Height
	Local Government Buildings	Foundation Material, Floodproofing, Base Floor Height
	Federal Buildings	Foundation Material, Floodproofing, Base Floor Height
	Bulkheads	Height, Condition at Mudline, Drain Locations
Transportation	Roads	Road Type, Washout Risk, Traffic Volume
	Ferry Terminals	Height, Wave Height Experienced, Traffic Volume
	Wharves/Docks	Height, Wave Height Experienced, Traffic Volume
Utilities	Electric Substations	Height, Submersibility, Protection of Electrical Components
	Power Lines	Depth/Height, Protective Casing, Material Strength
	Fuel/Gas Systems	Depth, Submersibility, Access Ports
	Fuel/Gas Storage	Depth/Height, Size, Valve/Pipe Material
	Power Transformers	Height, Submersibility, Power Destination
	Pump Stations	Submersibility, Protection of Electrical Components, Depth
	Distribution Systems	Submersibility, Protection of Electrical Components
	Stormwater Systems	Access Ports, Drain Locations, Outlet Height
	Sewer Systems	Access Ports
	Communications	Cable Protection, Depth/ Height
All	Flood Zone, Age, Condition, Elevation, Building Material, Purpose, Previous Damage, Monetary Value	

Within each sector, critical infrastructure can be classified as either soft or hard. Soft infrastructure refers to all of the institutions that serve to maintain the economic, health, cultural, and societal standards of a society. Some examples include civil service rules, public regulations, education systems, government operations, law enforcement, and emergency services. Hard infrastructure includes the large physical networks necessary for the society to function—buildings, roads, bridges, and energy systems (Bruce, Funkhouser, Hamm, Johnson, Leight, Martinelli, & Taylor, 2013).

Critical utilities infrastructure, which includes oil refineries, transport terminals, pipelines, and storage facilities on the East Coast, is vulnerable to flooding from sea level rise and storm surge. It is predicted that, "between 1992 and 2060, the number of energy facilities exposed to storm surge from a weak (Category 1) hurricane could increase by 15 to 67 percent under a high sea level rise scenario" (Allen and Dell, 2015, p.3).

Several different components of storm surge—wave action, salt-water damage, and coastal inundation—can damage a piece of infrastructure. These factors could lead to physical destruction, corrosion, or malfunctions that could leave a piece of infrastructure permanently compromised or completely inoperable.

In New York City, for example, flooding associated with storm surge due to Hurricane Sandy extensively damaged shoreline drains, causing roadway and sewer filtration systems to fail (Burden, 2013). Most electrical infrastructure is not designed to come in contact with large amounts ocean water, and is therefore prone to being damaged by storm surge. Damage to electrical infrastructure from salt-water inundation is extremely severe because salt reacts with different surfaces to cause corrosion. When critical infrastructure, such as an electricity grid, is impacted by storm surge, it greatly affects the lives of the people in the afflicted communities. On the Eastern Seaboard in 2012, Hurricane Sandy caused more than $68 billion in damage, mostly to the power supply. Not only did many residents and businesses lose power for several days, but many hospitals in the Manhattan area were also severely affected by loss of both primary and backup power (Schwartz, 2013).

2.3 • Remediation of Storm Surge

The National Oceanic and Atmospheric Association (NOAA) defines coastal resilience as the "ability of a community to 'bounce back' after hazardous events such as hurricanes, coastal storms, and flooding, rather than simply reacting to impacts" (What is resilience?). Various mitigation and planning techniques are often implemented with the help of GIS flood mapping in order to minimize future damage and enhance resilience.

2.3.1 • Enhancing Resilience

NOAA provides incentives to coastal cities for infrastructure protection through a coastal resilience grant program, which encourages communities to enhance resilience through advance planning and protective measures (NOAA 2015 Regional Coastal Resilience, 2015). When contemplating which strategies to implement, planners must consider the cost of implementation and ongoing maintenance, the effects that the measures would have on nearby land, and the historical success of each possible tactic. Generally, large structures like seawalls and bulkheads are more advantageous in areas that are highly developed, while floodproofing, modifying, and relocating infrastructure is better suited to less developed and environmentally sensitive areas (Kirshen, Knee, & Ruth, 2004). There are many mitigation tactics: natural systems protection, structure and infrastructure projects, floodproofing, elevation, and relocation.

Natural Systems Protection

Beach nourishment is one of the best natural approaches that can be taken to alleviate the effects of storm surge. Beaches are only shaped to withstand typical day-to-day wave depth and intensity; thus, adding more sand on beaches or creating sand dunes are strategies that can increase the peak height of these beaches or dunes in order to prevent water from breaching the crest of the sand in the event of a large storm. In 1989, Hurricane Hugo displayed how the sheer volume of added sand has the potential to affect the strength and durability of the dunes. During this hurricane, only areas that had dunes greater than 50 feet wide and 23 feet high were sufficiently protected from the storm, while narrower or lower areas were heavily damaged (Stauble, D. K., Seabergh, C. W., Hales, Z. L., 1991). The cost of sand for these dunes is roughly $20 per cubic foot (Bourne Consulting Engineering, 2009), so beach nourishment over time can become an expensive ongoing endeavor. It is especially ineffective as a primary method for preventing storm surge damage in areas that have minimal beach space with which to work.

Structure and Infrastructure Projects

Implementing or improving seawalls and bulkheads are among the most commonly used strategies for reducing the impact of storms on critical infrastructure in areas where beach nourishment alone is infeasible. Seawalls are built as a barrier to separate large waves from impacting the land behind it and causing damage to soil or any hard structures. Bulkheads, on the other hand, primarily retain the soil elevation and provide minimal protection from storm surge, although they still alleviate some of the wave action.

The effectiveness of seawalls was dramatically evident in the Bay Head & Mantoloking area of New Jersey during Hurricane Sandy. Houses unprotected by seawalls were heavily damaged, while those that were protected suffered less damage (Irish, J., P. Lynett, R. Weiss, S. Smallegan, and W. Chen, 2013). Depending on the materials used, and on the height and the width of the wall, the average cost of building a seawall ranges from approximately $600,000 to $4.3 million per mile (U.S. Army Corps of Engineers, et al., 2014). The most frequently used materials for constructing seawalls and bulkheads are wood, cement, large rocks, and steel. The downside to implementing seawalls is that they redirect waves to an adjacent shoreline, increasing erosion and potentially damaging nearby areas. Also, seawalls are prone to erosion and need to be repaired and modified over time, which increases costs. Some key factors in determining whether a seawall or a bulkhead is appropriate for a given location are: the topography of surrounding land, soil properties, the value and nature of the land use behind the structure (e.g., urban, industrial, or rural), and water levels surrounding the structure (Evaluating the Condition of Seawalls/Bulkheads). Seawalls, bulkheads, and other hard structures are essential for minimizing the amount of storm surge that hits land; however, they are usually supplemented by other tactics, as these hard structures are often not enough to entirely prevent storm surge damage.

Floodproofing

There are many approaches to protect a building from storm surge depending on its unique situation. In particular, there are several floodproofing strategies that have been historically used.

In many sources the term "floodproofing" is used to describe strategies of dry floodproofing. Dry floodproofing involves modifying a structure to prevent water from entering. A common technique is to apply sealants to the siding and foundation materials to keep water out. Elements passing through the walls, such as a pipes and drains, are also sealed to prevent water seepage. Backflow valves can be installed on pipes leaving the structure. These one-way valves prevent floodwater from flowing the opposite direction through an outbound pipe (Dry Floodproofing, 2014). A third option is to apply a plastic wrap around exterior walls. This plastic stops water from reaching the building with any seepage drained away to a pump, as seen in Figure 6 (Flood Wraps and Temporary Shields, 2015). The cheapest, and often most ineffective, technique is the use of door dams and sandbags. Door dams are panels that are anchored to doorways to provide additional protection to the entryway. Sandbags are used in conjunction to help seal the outer edges of the dams (Floodproofing Non-Residential Buildings, 2013).

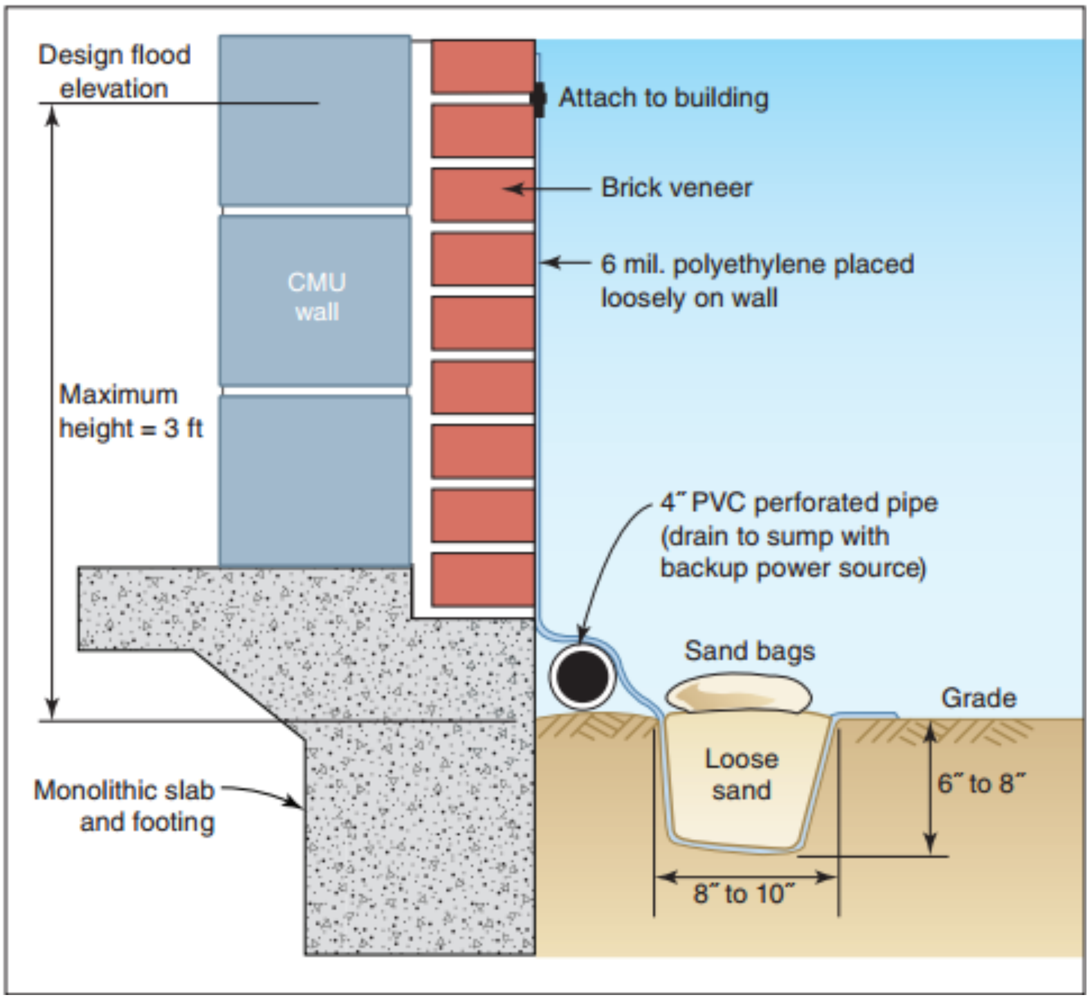

Figure 6: Model of a Building Protected by a Plastic Wrap and Drainage System

Adapted from http://www.fema.gov/media-library-data/9a50c534fc5895799321dcdd4b6083e7/P-936_8-20-13_508r.pdf, Page 4-27

Wet floodproofing, by contrast, allows water to enter the structure, but protects specific systems rather than the entire structure. These preventative measures do not completely eliminate flooding in the structure; rather, they curtail damage and expense. Wet floodproofing is significantly cheaper than dry floodproofing and can be completed in a modular fashion, with systems being protected individually to create greater overall protection. The most effective measures entail raising critical electrical and mechanical systems to areas above the flood zone (Wet Floodproofing, 2014). Another measure entails raising the height of electric outlets above the flood height and wiring them from the top down to reduce the amount of floodwater exposure to electrical components (Floodproofing Improvements for Walls and Floors, 2014).

In many buildings, openings are installed in foundation walls to allow water to move freely through the building's lower levels, thereby decreasing the hydrostatic and hydrodynamic loads applied to the structure and allowing for increased drainage rates to reduce damage and contamination. Another very popular wet floodproofing technique entails using submersible basement sump pumps that aid in draining water to reduce damages (Wet Floodproofing, 2014).

An external barrier system is another effective technique used to prevent floodwaters from even reaching a structure. When other strategies are too expensive, permanent floodwalls can be constructed around the infrastructure. They are designed to protect from floodwaters often greater than 4 feet, and prevent debris from causing structural damage (Floodwalls, 2014). Inflatable barriers are a temporary option accomplishing the same purpose. They consist of long tubes that are filled with water and placed around a structure to act as a solid wall. They can be deflated and reused when necessary (Water-inflated Barrier Series, 2015).

Floodproofing is usually recommended as a mitigation tactic if flood heights are expected to be below 3 feet. If anticipated flooding will exceed 3 feet, or will occur repeatedly, elevating the structure is preferable.

Elevating

Elevating critical infrastructure is among the most straightforward solutions when dealing with storm surge damage. The National Flood Insurance Program (NFIP) encourages the use of structures that are properly sealed, constructed with water resistant materials, and located above design flood level (Jones, 2009). The Massachusetts Departments of Public Safety (DPS) and Environmental Protection (DEP) have revised Appendix 120.G of the 7th Edition of the

Massachusetts Basic Building Code to conform to the NFIP regulations in order to ensure that buildings will be able to withstand floodwater, high velocity wave runup, and wave-induced erosion (Protecting Coastal Property from Major Storm Damage).

Elevating infrastructure is a common tactic used to prevent excess water contact. Six techniques have been devised for raising a structure, with the choice among them dictated by factors such as magnitude of elevation, foundation type, wall type, hazards experienced, and means of access to the building.

The first technique involves extending the foundation walls of a building with a basement or crawlspace. Holes are cut into the foundation to allow large raising beams to pass through the entire structure. The beams are run under the original floor and are then lifted off of the foundation to the desired height using hydraulic jacks. New foundation walls are built up to meet the new floor height.

A second technique, often used on brick buildings, extends all walls of the structure. The roof of the building is first removed along with doors and windows. Window and door locations are raised to the desired height by taking brick from above these openings and adding it below; the roof is then replaced. A new floor is constructed to meet the change in elevation.

Another technique is suited to a masonry building that cannot be extended, or to a structure to be elevated over 6 feet. The best option is to abandon the lower floor, relegating it to use as a garage, storage area, or access point. The structure itself is not physically elevated, but the lower floor's valuable contents, utilities, and functions are repositioned to higher levels above the flood zone. The structure still can be insured, even though the lower floor is vulnerable to damage.

Two techniques can be used to raise a building that is slab-on-grade. One possibility is to keep the original cement slab by placing the raising beams below the slab. The entire structure and its slab are then raised to the desired height and the foundation walls are extended to the new elevation. The other option is to raise the building without the cement slab by cutting the walls away from the slab. The original slab will remain at ground level, which necessitates constructing a new floor once the building is raised. Raising beams are placed above the slab and will only lift the walls. After the structure walls are lifted and the new floor is built, the foundation can be extended to the new height.

Lastly, a building can be elevated onto support columns. Here, the building is raised on support beams; structural supports are placed underneath using columns, piers, posts, or pilings.

This approach is very common in coastal communities, as it allows for the greatest amount of water flow below the building (Homeowner's Guide to Retrofitting, 2014). Figure 7 shows an example of this type of elevation in Nantucket.

Figure 7: House on Walsh Street, Sitting on Beams and Structural Supports

All of the above options serve to minimize the structure's contact with floodwater. In all cases, holes are left under the building, leaving space between the floor and ground levels. This allows for floodwater to flow through the building's foundation, reducing stresses on the structure caused by water pushing on its face (Homeowner's Guide to Retrofitting, 2014).

If elevation is to occur on commercial and residential buildings, they must be raised above the 100-year floodplain to comply with regulations in order to receive flood insurance. The magnitude of elevation depends on the most up-to-date FEMA flood maps for that area. For all structures controlled by the federal government, elevation above the 500-year flood zone is mandated. This applies to new construction or structures undergoing major structural renovations. The additional height requirements may affect the cost effectiveness of building a new, or remodeling an old, federal structure. It is also important to consider elevating external systems not required for flood insurance such as generators, storage tanks, or electrical components.

The combination of both elevating a structure and sealing it properly offers the best prospect of minimizing water damage from intrusion. Unfortunately, in some worst-case scenarios where storm surge damage is too large and frequent, the most practical solution is to abandon the structure and rebuild elsewhere. Leaving the infrastructure in a flood prone area may ultimately prove more costly and inconvenient than relocating it in advance of a catastrophic event.

Relocating

When planning to rebuild a structure in a new area, it is essential to know the flood patterns in order to plan accordingly. The NFIP under the authority of FEMA is responsible for identifying and mapping flood hazards in the United States. In order to understand the potential threats of flooding in a given area, FEMA has defined several types of "zones." A common term that is used when classifying potential flooding areas is a base flood or 100-year flood. This is defined as a flood that has a 1% annual chance of being equaled or exceeded, and it is the baseline for the NFIP to determine flood insurance costs (Base Flood). A base flood elevation is often denoted to represent the height of water during a base flood. It is also important that an infrastructure's critical elevation—the elevation in which floodwater has the potential to damage a critical component of the infrastructure—should be higher than the base flood elevation. Water typically enters buildings at floor level, and therefore the *base floor* elevation is usually a building's critical elevation. Areas that fall into a base flood or 100-year flood category might be labeled as A or V zones, while areas that only have a 0.2% annual chance of being flooded—a 500-year flood—could be labeled as C or X zones. Based on which zone a piece of infrastructure is located in, appropriate insurance and protection will be necessary or required.

When choosing relocation as a mitigation tactic, two possible strategies can be considered. One is to relocate a structure by physically lifting the building from one lot and moving it to a new site; this is typically done in areas that are subject to significant erosion. This already arduous and expensive option is made even more costly by the unique land costs associated with limited building space, such as that of an island. A second, often more convenient, option is to change the function of the building, especially when buildings are non-conducive to physical relocation. During major storms, some critical town functions can be briefly relocated to safer locations without a major disruption of service. With effective advance planning, it would be very beneficial to move certain town functions outside of the flood zone to avoid these temporary shifts.

2.3.2 • GIS Flood Mapping

Most coastal towns use Geographic Information Systems (GIS) to plot information that is vital in the assessment of coastal flooding and its impacts on infrastructure. These systems are capable of keeping track of multiple layers of data in one database and displaying them on a single interface. This allows for easy access to all of the information about a given area including elevations, storm surge paths, and both current and projected sea levels (Figure 8).

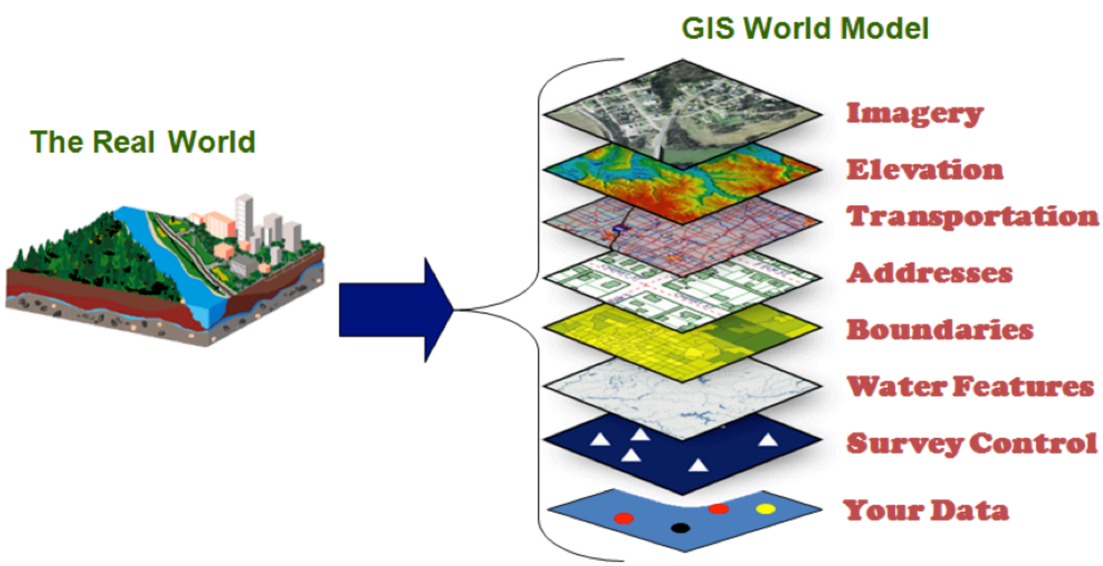

Figure 8: Geographic Information System

Adapted from http://henrico.us/gis/

GIS proves to be a useful tool for mitigation and planning purposes because it accurately depicts the areas in which there is an overlap with flooding and critical infrastructure. It is also commonly used with storm surge modeling software to further enable cities to see how storm surge reaches the shoreline over a period of time. For example, research has been done along the New York and New Jersey shorelines by overlaying hydrodynamic models on GIS software to plot storm surge elevations projecting as far into the future as the year 2080 in order to assess the extent of inundation due to storm surge (Kim, N., George, B., & Simmons, P., 2013).

2.4 • Nantucket

Nantucket Island lies roughly 30 miles off of the south coast of Cape Cod, Massachusetts and is approximately 48 square miles in size. As an island, Nantucket is inherently more prone to the impacts of storms and storm surge than mainland Massachusetts is. During Winter Storm Juno in January 2015, for example, over 12,000 customers of National Grid lost power, 600 of them for two days, due to the combination of snow, ice, and coastal flooding (A Tough One, 2015). Large storms such as Juno shut down all ferries to and from the island, limiting the capacity of essential companies like National Grid to address unanticipated needed repairs and leaving many Nantucket residents without power. It is therefore essential that critical infrastructure be maintained in operational condition, especially in the summer when the population reaches its peak, by using resilience tactics to alleviate the damage caused by storms, and storm surge in particular.

2.4.1 • Infrastructure

In terms of emergency management, one of the greatest areas of local concern is the Island's downtown area, which is most prone to flooding and where critical infrastructure is situated. This includes Town offices, ferry terminals, fuel storage facilities, and key electrical and telecommunications infrastructure from the mainland. Figure 9 shows the 100-year and 500-year flood zones overlaid on the street network within our study area. The area of interest is bound by Easton Street and Chester Street to the north, Center Street, Main Street, and Union Street to the west, the Goose Pond Trail to the south, and Nantucket Harbor to the east. Almost the entirety of our area of interest is in this critical flood zone.

All of the waterfront properties on Washington and Easton Streets are in the 100-year flood zone and are prone to flooding. Some of these properties are even in the velocity zone—the area in the 100-year flood zone that can also be affected by storm-induced wave action (Zone V). This part of the town includes several government offices and other key buildings that are deemed critical.

Figure 9: FEMA Flood Map with Boundary

Adapted from http://www.mapgeo.com/NantucketMA/

The docks and transportation wharves in the blue area of Figure 10—which shows the mix of residential, commercial, and industrial usage in our boundary—are used for moving supplies, which is especially important before and after a major storm. Commercial areas include critical utilities and communications infrastructure. In the 500-year flood zone, effects of storm surge flooding extend even further inland to higher elevations and have the potential to put even more stress on buildings and infrastructure. This results in damage to an even larger number of commercial areas and public buildings, magnifying the effects of the storm, as even more pieces of infrastructure in the downtown will be damaged.

After a storm, the Town of Nantucket fills out an Initial Damage Assessment (IDA), which is an estimate of the expected damage costs caused by a storm. This estimate encompasses the cost of emergency protective measures, debris removal, and physical damage to public infrastructure. If the total of the IDA reaches $36,500 for Nantucket County, Nantucket is eligible for state funds to help cover costs. If all of the Massachusetts' counties reach a specified threshold, the governor can announce a state of emergency and federal funds can be dispersed at the President's discretion. These monies are then distributed to the respective counties that are eligible for funding. After the preliminary IDAs, detailed reports of contracts, receipts, and overtime are collected, detailing the expenses of the storm. These are submitted, and the county is reimbursed for 75% of total damage costs.

Over the past several years, storms and storm surge have taken a major toll on Nantucket. After Hurricane Sandy, the total estimated damages were approximately $125,000, with $90,000 of these damages being to the Washington Street piers (Fronzuto, 2012). After the nor'easter Juno, the total estimated damages were $1,700,000, and $1,200,000 of the damages were inflicted on the town pier (Fronzuto, 2015). Massive storm damages such as these are likely to occur more frequently in the future, due to sea level rise and the increase in the frequency of severe storms; therefore, preventative planning through mitigation tactics will be essential in relieving the immense cost of storm damage.

Figure 10: GIS Map with Land Use

Adapted from http://www.mapgeo.com/NantucketMA/

2.4.2 • Emergency Management

The Nantucket Emergency Management Agency (NEMA) works to protect the people and the assets of the island in the "event of a natural or man-made disaster by effective planning and coordinated use of all personnel, equipment, available shelter, and any other resources during an actual emergency" (NEMA, 2015). NEMA is also responsible for providing financial recovery from storms and creating an emergency plan for disasters to minimize risk to people and property.

The emergency management team has already worked hard to prepare the Island from further damage. In 2013, the Town of Nantucket became the first of the Massachusetts coastal/island towns to be certified as StormReady (NEMA, 2015). StormReady is a voluntary program sponsored by the National Weather Service to encourage communities and commercial sites to prepare themselves for severe storms. For Nantucket to be recognized as StormReady, the emergency management team worked to set up redundant communications systems to find multiple ways to send emergency alert messages to the public and to inform the population of the importance of public readiness and emergency plans (About StormReady, 2015).

During a storm event, the tide rises, and if it exceeds 5 feet, it is called a plus tide. The National Weather Service would contact the NEMA for possible flood inundation at 5+ feet. When there is a plus tide, for example, the floodgate at Children's Beach Boat Ramp is implemented to alleviate wave action and to slow flooding on Harbor View Way. NEMA may also consider evacuating low-lying areas if emergency crews would not be able to access the residents in those areas.

Members of NEMA and other departments on the island worked together to form a committee to evaluate the safety of town-owned infrastructure and roads on the island. The Town of Nantucket created the Coastal Management Plan, which evaluated the conditions of town-owned infrastructure and suggested different components that needed protection. One suggestion was to raise the bulkheads near Easy Street to prevent splash-over during storms and to increase the number of storm drain outlets for proper drainage. This preliminary report allowed for further implementation of erosion and hard structure armoring of town-owned land in the future (Town of Nantucket, 2014).

While NEMA and the Town have explored ways to enhance preparation for storms, serious concerns remain for the integrity of the Island's infrastructure. There will likely be future storms that bring storm surge damage as predicted by recent studies on climate change and sea level rise. It is of particular importance that preparations be made in the downtown area, which is the central hub for tourism and where much of Nantucket's critical infrastructure is located. Our analyses identified and prioritized the importance of different components in the area and have suggested ways to protect these components in the future. Our analyses and supporting information, along with the mitigation and resiliency strategies we present, offer NEMA a solid foundation for devising an overall plan to protect the Island's critical infrastructure.

3 • Methodology

This project identifies and evaluates potential ways to protect Nantucket's downtown critical infrastructure from storm surge and offers recommendations for mitigating future adverse impacts. Our project had four main objectives:

1. Evaluate past and current practices, along with recognized best practices, for protecting critical infrastructure to determine what approaches have proven to be most successful;
2. Identify and characterize critical infrastructure in the defined downtown study area;
3. Evaluate the advantages and disadvantages of alternative planning, protective, and mitigation strategies for different infrastructural elements; and
4. Formulate and prioritize and recommendations for the future.

3.1 • Objective 1: Evaluate Past, Current & Best Practices

We supplemented our background research with a series of interviews with knowledgeable local authorities to determine current and best practices for protecting critical infrastructure.

Our sponsor from the Nantucket Emergency Management Agency, Dave Fronzuto, was most helpful in providing information about how Nantucket has dealt with storm surge in the past. We had scheduled weekly meetings with both him and our project liaison, Peter Morrison, where we discussed the specific logistics of our project and how we could acquire the information and tools to reach our goal. For our interviews, we initially sent out emails explaining the nature of our research project and the interviewee's rights (Appendix A), and then asked to meet for an in-person interview. We began each interview by repeating the interviewee's rights and then briefly describing our project and goals. For each interview, we informally followed a list of previously developed interview questions for guidance in our discussion with each interviewee (Appendix A). We assigned one member of the group responsibility for asking questions and another member responsibility for recording minutes for the interview; all members were free to speak and pose questions. Most interviews took 30 to 60 minutes. Without exception, all of our interviewees were cooperative and open in their answers to all of the questions; they also invited us to email them with any further questions that arose. In several cases, we did follow up with an email request for relevant records that they had on file. Appendix B documents this sample of interviewees, which includes their name, title, interview date, and reason for the interview.

3.2 • Objective 2: Identify & Characterize Critical Infrastructure

To systematically identify and characterize the Town's critical infrastructure, we began by defining our study area based on FEMA flood maps and identifying the critical infrastructure within it. We developed, tested, and refined our checklist for gathering many pertinent pieces of information about each element of infrastructure before implementing the finalized protocols in the field.

3.2.1 • Define Area of Interest

During our initial meeting with our sponsor, we defined our area of interest as Easton Street and Chester Street to the north, Center Street, Main Street, and Union Street to the west, the Goose Pond Trail to the south, and Nantucket Harbor to the east. We also included the Natural Resources Department building at 2 Bathing Beach Road in our list of critical infrastructure, although it sits north of our boundary. As previously shown in Figure 9, this boundary approximates the area that is likely to be most adversely affected by floods and by storm surge of different sizes and strengths. This figure features the 2014 FEMA flood map for the downtown area, which delineates the flood zones for the 100- and 500-year floods. By using a topography overlay available on Nantucket's public GIS, we determined that the 100-year flood line follows an approximate elevation curve of 10 feet above sea level.

3.2.2 • Develop Operational Definition of Critical Infrastructure

As discussed in the background section, critical infrastructure can be defined in several ways. We explored this point in an initial meeting with the Emergency Coordinator, Dave Fronzuto. The definition he offered is: "all assets, either public or private, that are essential to the community." He continued, "if these assets are damaged or destroyed by storms, floods, earthquakes, or tsunamis, they will cause service disruption and a loss of critical transportation, evacuation, and emergency service routes, hindering the Island's ability to recover and respond, before or after a disaster." Based on this definition, we adopted the following operational definition for our purposes: critical infrastructure is any type of infrastructure that is essential to the day-to-day operations of a town or city and its residents.

Table 2 provides examples of various types of such critical infrastructure situated within the study area. We have categorized them here by sector: built infrastructure, transportation, and utilities.

Table 2: Critical Infrastructure Characterization

Sector	Infrastructure Involved
Built Infrastructure	Private buildings, municipal offices/buildings, federal buildings, bulkheads
Transportation	Roads, ferry terminals, wharves, docks, boat ramps, parking lots
Utilities	Electric substations, sewage pumping stations, stormwater systems, sewer systems, telecommunications

Being an island, Nantucket has certain unique elements of infrastructure that are deemed critical. These include the ferry terminals, which house the main source of transportation to the mainland, and underwater electric cables, which are the primary source of electric power on the island. Any damage to these unique pieces of infrastructure due to storm surge or other severe events would adversely impact most of Nantucket's residents, and severely so over any prolonged time period. Other pieces of infrastructure are not unique to Nantucket: roads, oil storage tanks, sewer lines, and certain public buildings (such as the Town's Finance Department building). However, any short- or long-term disruption to the services they provide would severely impact the community.

Local businesses, which are the main driving force behind Nantucket's booming tourism-based economy, are not typically deemed to be *critical*, as they are often not essential to the immediate human survival of the residents in the community. Under our operational definition, however, some qualify as critical businesses—for example, the downtown Stop & Shop. It is the primary source of provisions to the downtown population of residents and, during summer months, to the many thousands of tourists. Any prolonged suspension of its business (for example, shelves emptied after several days of power loss and/or suspended ferry service) surely would "disrupt the day-to-day operations of the Town and its residents."

3.2.3 • Develop & Refine Protocols for Identifying & Characterizing Critical Infrastructure

We developed three data-gathering checklists to guide us in collecting data in the field. These initial protocols reflect the findings from our literature review and our consultations with our sponsors, advisors, and other experts noted above. Each checklist corresponds to one type of critical infrastructure shown in Table 3—utilities, built, and transportation. Figures 11, 12, and 13 show these checklists and their formats that we used to assemble necessary data.

These checklists are intended to serve as summary sheets for each individual piece of infrastructure. We designed them to capture and display information gathered both from previous research and from our field observations. Their design and further refinements progressed throughout our initial data collection, subsequent field observations, interviews with experts, and reviews of available GIS data and other town records. We continued to refine the checklist format as we incorporated information from various sources and as we cross-checked data. Our checklists had both generic information pertaining to all pieces of infrastructure and specific information pertaining to a specific infrastructure type.

Our formulation and refinement of checklists involved various steps. Initially, we drew upon Nantucket's Geographic Information System (GIS) database to pinpoint the specific locations of certain pieces of infrastructure that met our operational definitions and categorized each by type. GIS technology—specifically the topography layer—enabled us to assign an infrastructure's elevation above sea level. It also furnished the infrastructure's assessed value, according to town property tax records. We used the North American Vertical Datum of 1988 (NAVD88) as a reference point for all of these elevations to maintain consistent data. From the Nantucket Assessor's website, we obtained the address, parcel number, year built, owner, and building materials for each piece of infrastructure. In some instances, we deemed the year last modified to be preferable to the year built. Such background information is included to afford a full understanding of the infrastructure and its physical characteristics, such as the building materials (a useful indicator of the potential need for repairs).

While this protocol met our needs for most pieces of infrastructure, some important information was not listed. In those instances, we contacted the appropriate knowledgeable authorities to obtain further known details. For example, when the full value of buildings and their contents were unknown, we consulted the Nantucket Assessor, Ms. Dilworth, and the Nantucket Accounting Clerk, Ms. Lapiene, who furnished detailed documents providing building costs and the buildings' fixed assets.

To determine which items of critical infrastructure were located in the flood-prone areas of downtown Nantucket, we used the updated 2014 FEMA Flood Maps. By overlaying the flood maps on the baseline maps of infrastructure in Figure 9, we determined which pieces of infrastructure are situated in the velocity (VE) zone, the 100-year (AE) zone, and the 500-year zone (0.2%). In our checklists, we also included the FEMA flood map number for each piece of infrastructure, for ease of reference by users.

To capture information for the previous damage section, we contacted the appropriate experts including, but not limited to, the Building Commissioner, Assistant Town Manager, Director of the Department of Public Works, U.S. Coast Guard Brant Point Senior Chief, Emergency Management Coordinator, and Nantucket's National Grid Manager. Most notable past damages have been caused by the Winter Storm Juno in early 2015 and the No Name Storm of 1991. Available information on past damages proved to be spotty, due to the lack of historical documentation; accordingly, we relied on oral recollections of knowledgeable authorities. If there was known previous damage, we recorded that as "yes" and then proceeded to search for further details evidenced in building permits dating back to 1972. These permits, maintained at the Planning Office, are objective historical records of modifications made soon after the above 1991 and 2015 storm events. They had the potential to supplement what limited information we could obtain from other sources.

Based on our interviews and our own visual observations, we determined what types of proactive measures had been taken to protect each piece of infrastructure in the event of a severe storm. We identified items like flood dams or barriers and asked key informants (i.e., our interviewees as well as employees at particular facilities) if they use other protective measures, such as sandbags, prior to a major storm.

For the "observation of current condition" section of the checklist, we performed preliminary visual inspections. We noted water damage, such as rotting, paint chipping, rust, and cracking at the foundation. We caution that these are our own subjective assessments of condition, by undergraduates without the necessary credentials and expertise to perform professional assessments.

Name:

Type:		Year Built / Last Modified:	
Location:		Height (feet NAVD88):	GIS: Surveyed:
Owner:		Value	

Velocity Zone:	Y / N	100-Year Zone: (AE Flooding Zone)	Y / N	500-Year Zone: (0.2% Annual Flood)	Y / N

GIS Parcel Number:		FEMA Zone:	

Building Materials:

Observations of Current Condition:

Previous Damage:

Yes / No

Critical Elevation:

GIS:	Surveyed:

Protective Measures in Place:

Other:

Description of Structure/Measurements: Basement: Location of Critical Components: Number of Access Points:

Figure 11: Utilities Infrastructure Checklist

Name:

Type:		Year Built / Last Modified:	
Location:		Height (feet NAVD88):	GIS: Surveyed:
Owner:		Value	

Velocity Zone:	Y / N	100-Year Zone: (AE Flooding Zone)	Y / N	500-Year Zone: (0.2% Annual Flood)	Y / N

GIS Parcel Number:		FEMA Zone:	

Building Materials (foundation, walls):

Observations of Current Condition:

Previous Damage:

Yes / No

Base Floor Elevation:

GIS:	Surveyed:

Protective Measures in Place:

Other:

Description of Structure/Measurements: Observations of Location: Basement: Location of Critical Components: Number of Access Points:

Figure 12: Built Infrastructure Checklist

Name:

Type:		Year Built / Last Modified:	
Location:		Height (feet NAVD88):	GIS: Surveyed:
Owner:		Value	

Velocity Zone:	Y / N	100-Year Zone: (AE Flooding Zone)	Y / N	500-Year Zone: (0.2% Annual Flood)	Y / N

GIS Parcel Number:		FEMA Zone:	

Building Materials:

Observations of Current Condition:

Previous Damage:

Yes / No

Protective Measures in Place:

Traffic Volume:

Other:

Description of Structure/Measurements: Observation of Location: Number of Drains:

Figure 13: Transportation Infrastructure Checklist

To determine the critical or base floor elevation for a piece of infrastructure, surveyor Frank Holdgate obtained the elevation of the ground at the base of a piece of infrastructure. He used a surveying tool, called Leica Viva GS14, which utilizes a highly accurate gravity-based global positioning system (GPS) monitoring process. We recorded this measured elevation as the surveyed elevation for the infrastructure, and from it we measured the height of the base floor with a measuring tape to 1/10th of an inch of accuracy. Finally, we determined the base floor elevation by adding the elevation of the ground to the height of the base floor. In addition to the surveyed height, we used a GIS topography layer to estimate the ground elevation at a piece of infrastructure then measured to the appropriate base floor or critical elevation with a tape measure. We retained both measurements to detect any difference between them.

In the checklists, we included descriptions of the structure and associated measurements, along with observations of its location. For pieces of infrastructure without floors or for which the floor height is not the critical elevation, we instead measured the height to "critical" components with a measuring tape. "Critical" components are defined as anything that will seriously impair the functionality of building operations. We also examined the condition of the surrounding land and noted the slope, which would affect how water would flow to or away from the piece of infrastructure. We photographically documented the physical arrangement, location, and condition of infrastructural elements and included these photographs in the summary database.

Inherent differences among the three sectors dictated certain differences in the checklists. The utilities checklist (Figure 11) closely resembles the built infrastructure checklist, with one main difference. We focused in the utilities checklist on measuring the critical elevation rather than the base floor elevation, since many critical components are located externally. However, we did record the base floor elevation wherever relevant.

For the utilities checklist (Figure 11) and the built infrastructure checklist (Figure 12), we recorded the presence or absence of a basement, because a basement is often the first area affected by a storm surge flood. For each building, we also recorded the number and locations of access points, because that information pertains to possible mitigation strategies. Through our data gathering process, we also recorded the locations of critical components based on both our own visual observations of these components and querying authorities of each building operation as to what aspects about the building they deemed to be critical. Understanding where these components are located greatly enhances our ability to make an accurate risk assessment for that piece of infrastructure.

The transportation checklist (Figure 13) captures information unique to traffic flow per unit of time, as well as the number of drains associated with the piece of infrastructure. Knowing the magnitude and intensity of traffic flow highlights the importance of particular pieces of transportation infrastructure when assigning potential risk. We acquired a sample of peak-hour midday traffic flow data from August 2007 from the Nantucket Planning Office for several roads in our study area. (Harbor View Way and parts of Easton Street are noteworthy exceptions.) In our checklists, we regard this data as roughly indicative of the volume of vehicular traffic on a road, with the important caveat that such volume varies greatly by time of day, season, and road location. The Steamship Authority and Hy-Line ferries are the main forms of transportation to and from the island, and we acquired data for the number of passengers during both the on- and off-season from company representatives, when available. These passenger counts document the importance of the ferry transportation function, as indexed by number of users. Traffic flow data for the public parking lot on Washington Street was obtained through visual inspection and from interviews. To record the number and locations of drains in our study area, we drew upon a stormwater flow map furnished by the director of the Department of Public Works. As previously mentioned, we included a surveyed height as well as the GIS topographical height for all types of transportation other than roads (for which height readings would depend on where the measurement was taken on the road).

In addition to the checklists, we drafted written summaries of the infrastructure to expand upon the information contained in the checklists. These summaries presented further detailed information we deemed important to better understand the unique properties of a specific piece of infrastructure not fully captured by checklist measures. For example, we detailed previous damages and protective measures. The descriptions complemented the checklists by giving a quick summary of the infrastructure along with a narrative that amplifies facets not fully captured or explained in the checklists. They also provided a more thorough view of the infrastructure and its surrounding areas. Photographs of the infrastructure were added to give visual reference to the specific site. We included these descriptions, along with some of our recommendations, as part of our findings.

Appropriate data was entered into the GIS program after we collected information for each infrastructure. Nathan Porter, the GIS Coordinator for Nantucket, supplied us with pertinent GIS files from the Nantucket database including flood maps, parcel locations, topography, and building footprints. These files were loaded into our working project database to serve as a starting point for loading our collected data. Using the checklists, we were able add additional fields. The categories added were as follows: infrastructure name and sector, address, monetary value, ground elevation, base floor elevation, risk value, and appropriate FEMA flood map tile location. The data was input into an attribute table with relevant information tied to the correct infrastructure location. A second layer, displaying a red polyline border, was also created to show our original working boundary that defined our area of interest. Base maps containing street plans and names were downloaded from MassGIS, as well as a map of Nantucket using satellite images obtained from the Nantucket GIS database. These base maps created additional layers for reference and the satellite images added improved levels of detail for up-close viewing. When a specific location is selected for identification, relevant data appears on screen along with a page number referencing the viewer to the appropriate page in the summary database for further information.

The main objective of the GIS database was to display data visually. Each infrastructure on the map was color-coded based on its assigned sector type, and each risk area of the flood zones was color-coded to match the scheme found on the Nantucket GIS. When elevation and flood maps are overlain, the viewer can easily visualize the surrounding environment and each piece of infrastructure's proximity to potential risk. The GIS database serves as a visual reference with basic information about each piece of infrastructure.

3.2.4 • Determine Risk

Based on the collected data, we have assigned each piece of infrastructure a risk score, summarized in Table 3. The color-coded score categories show the likelihood of a piece of infrastructure being damaged by a 100-year storm surge versus the resulting consequence if that infrastructure were to be inoperable. The closer a piece of infrastructure is to the upper left-hand corner of the chart, the greater the risk it presents to the community by virtue of likelihood and consequence. For example, infrastructure that is very likely to experience a storm surge with potentially catastrophic consequences should be accorded close and immediate attention.

Table 3: Risk Categorization

Adapted from *Strategies for Promoting Resilience to Increased Coastal Flooding Along the Downtown Boston Waterfront*.

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

To generate this likelihood score, we incorporated factors such as the amount of damage the infrastructure has encountered in past storms due to water, along with the infrastructure's critical elevation. To determine the critical elevation of each piece of infrastructure, we compared surveyed measurements of the critical components of the observed infrastructure with their respective location within the 100- and 500-year flood zones, while we also analyzed the topography of the land. In addition, we took into consideration both the protective measures currently in place and the current condition of the infrastructure when providing this ranking metric. We incorporated all of these factors into an informed judgment of the comparative likelihood of severe damage to a given piece of infrastructure relative to others. Such judgment entails sequentially ranking one piece of infrastructure against others, to arrive at an ordinal ranking on each dimension (likelihood and consequence).

To illustrate our ranking on likelihood: A piece of infrastructure with a low critical elevation, situated in an area at very high risk of being damaged by flooding due to storm surge, and poorly protected or poorly constructed, was given a rank *A* (very likely). By contrast, its counterpart without most or all of those attributes was given a rank as low as *E* (very unlikely).

To illustrate our ranking on consequence: A piece of infrastructure that, if inoperable, would affect a large number of people, would incur high financial losses, and would invite significant health concerns, was given a rank *1* (catastrophic). By contrast, its counterpart that would not have such serious or widespread repercussions was given a rank as low as *5* (insignificant).

Likelihood is a one-dimensional concept; consequence is multifaceted. For the latter, we took into consideration the consequences of each piece of infrastructure being rendered inoperable for only a brief, or for a longer, period of time. The reason we focused on complete loss of functionality, rather than solely focusing on the impacts of storm surge-induced flooding, is that we wanted to present the consequence of a worst case scenario situation, so as to not understate the criticality of some pieces of infrastructure. For some infrastructure, criticality may increase exponentially with duration: a 48-hour power outage may be more critical than a 12-hour outage by a factor of 10, not 4, for example. We interviewed experts within the community to gain knowledge about the frequency of use of a certain piece of infrastructure, along with the infrastructure's role in the community. We drew upon the Federal Highway Administration's approach in gauging the severity of damage to a community, as shown in Appendix C, modifying it for those instances where we saw an obvious necessary refinement to fit our needs. Overall, a piece of infrastructure that would cause catastrophic problems if disabled or destroyed was given a prefix *1*, while infrastructure that would have an insignificant impact on the community if inoperable was given a prefix *5*. We included this assigned rank for each piece of infrastructure in each summary along with the rationale behind its ranking.

3.3 • Objective 3: Evaluation of Protection & Mitigation Strategies

Based on our background research, we identified two primary protection procedures for a piece of infrastructure: modification and relocation.

3.3.1 • Modification of Existing Infrastructure

Modifying existing structures to better withstand storm surge is an effective tactic, as it is often a quick remediation method to implement and has the potential to last several years. Some of the key components we looked at when proposing to modify a piece of infrastructure included what parts are being damaged and why they are being damaged. By understanding this, we were able to suggest ways to plan accordingly and to design infrastructure that will be less likely to be damaged. Some planning techniques include raising the height of critical components, implementing door dams, improving the foundation conditions through the use of sealants, and elevating the structure.

3.3.2 • Relocation of Infrastructure

Relocating infrastructure on Nantucket was an alternative strategy that did not involve physical modifications. Instead, money could be spent on moving the structure to a safer location. This preserves the integrity of the structure, especially if it has historical significance. For certain pieces of infrastructure that are immobile and can only be used in their current locations, such as the docks in the harbor, relocation was not a realistic option. Also, relocation can tend to be an expensive endeavor, and would not be a prominent option if the costs of repairing frequent damage do not prove to be greater than the cost of relocation.

A more reasonable alternative was relocating the *function* of the building, rather than moving the structure itself. The Town of Nantucket has a unique situation, in that it often moves the locations of town departments to accommodate changes in staffing and space requirements. This suggests that the functions have the ability to move, making it a reasonable option to relocate the most critical town departments outside of the flood zone.

3.3.3 • Evaluation

In order to evaluate which strategies will be most effective for a given piece of infrastructure, we analyzed the advantages and disadvantages of the various options. We investigated each piece of infrastructure to decide which components of the infrastructure would be at risk in the event of a flood, and how capable they would be of withstanding water contact before being damaged. Based on some of these factors, we were able to analyze which mitigation strategies would be most beneficial for future protection from storm surge.

3.4 • Objective 4: Identify Priorities & Recommendations

Once we compiled a list prioritizing each piece of infrastructure, we incorporated our evaluation of mitigation strategies to develop recommendations for the Town of Nantucket to use in future protection efforts. Our prioritization, based on the risk categorization chart, highlights the pieces of infrastructure that should be worked on first, and which are less of a priority. For example, infrastructure that required large amounts of funding and man-hours had a lower priority than something that would be a cheap and quick repair. Our recommendations provide the most effective strategies for future implementation, along with some of the obstacles that may be associated with this implementation. Aside from currently existing structures, our team also suggested preventive planning techniques for infrastructure that is to be built in the future, based on the previously researched best practices.

We have built a summary database that is available both in a binder in hard copy as well as digitally. This database consists of our checklists, summaries, risk rating, and recommendations for each piece of critical infrastructure.

4 • Findings

In this chapter, we will present our findings. These findings include our final infrastructure database, infrastructure checklists and descriptions, and ranking assessments for each individual piece of critical infrastructure.

4.1 • Database of Infrastructure

After several weeks of data collection, our team compiled a list of 26 pieces of critical infrastructure within our case study boundary, shown in Figure 14. While some of these pieces of infrastructure serve several purposes and have multiple physical attributes, we have designated each piece of infrastructure in a particular category, based on its sector: utilities, built infrastructure, or transportation, and have color-coded these accordingly. Note that small pieces of infrastructure, such as the Children's Beach Stormwater Pump Station are not visible at this resolution but are part of the GIS record. Of the 26 pieces of infrastructure we have studied, we have categorized 5 as utilities, 10 as built infrastructure, and 11 as transportation, as shown in Table 4.

4.2 • Infrastructure Checklists

Using the protocols described in Chapter 3, we collected data from observations of each piece of infrastructure in the field. We supplemented field observations with additional data gleaned from various sources, including interviews with local experts. In many instances, local experts accompanied us on our field observations to assist in interpreting the structures. The data were entered into the checklists presented in our summary database.

In some instances, we were not able to acquire all of the pertinent data. For example, we were unable to find building date and assessed value for the NRTA / Health Department building from either the Assessor's Office or the Planning Office. Similarly, paving histories for the roads were not known, so we were unable to specify dates as to when the streets in the study area were built or last modified.

Table 4: Infrastructure Database

Sector	Name	Address/Location	Ownership
Utilities Infrastructure	• Candle Street Substation	6 Candle Street	National Grid
	• Sea Street Pump Station	1 Sea Street	TON
	• Children's Beach Stormwater Pump Station	15 Harbor View Way	TON
	• Goose Pond Sewer Main	Under Goose Pond Trail	TON
	• Union Street Telephone Building	3 Union Street	Bell Atlantic
Built Infrastructure	• U.S. Coast Guard Station	10 Easton Street	United States
	• Town Administrative Building	16 Broad Street	TON
	• Sheriff's Office	20 South Water Street	TON
	• NRTA/ Health Department	3 East Chestnut Street	TON
	• Easy Street Bulkhead	Easy Street	TON
	• Stop & Shop	9 Salem Street	Stop & Shop
	• Marine Department/ Harbormaster's Office	34 Washington Street	TON
	• Finance Department	37 Washington Street	TON
	• Natural Resources Department	2 Bathing Beach Road	TON
	• Post Office	5 Federal Street	United States
Transportation Infrastructure	• Children's Beach Boat Ramp	15 Harbor View Way	TON
	• Straight Wharf (Hy-Line)	Straight Wharf	Scudder Family
	• Steamboat Wharf	Steamboat Wharf	State of Massachusetts
	• Tanker Dock	Between Old South Wharf and Commercial Wharf	TON
	• Town Parking Lot	Surrounds Finance Building on Washington Street	TON
	• Easy Street		TON
	• Harbor View Way		TON
	• Easton Street		TON
	• Lower Broad Street		TON
	• Washington Street		TON
	• Francis Street		TON

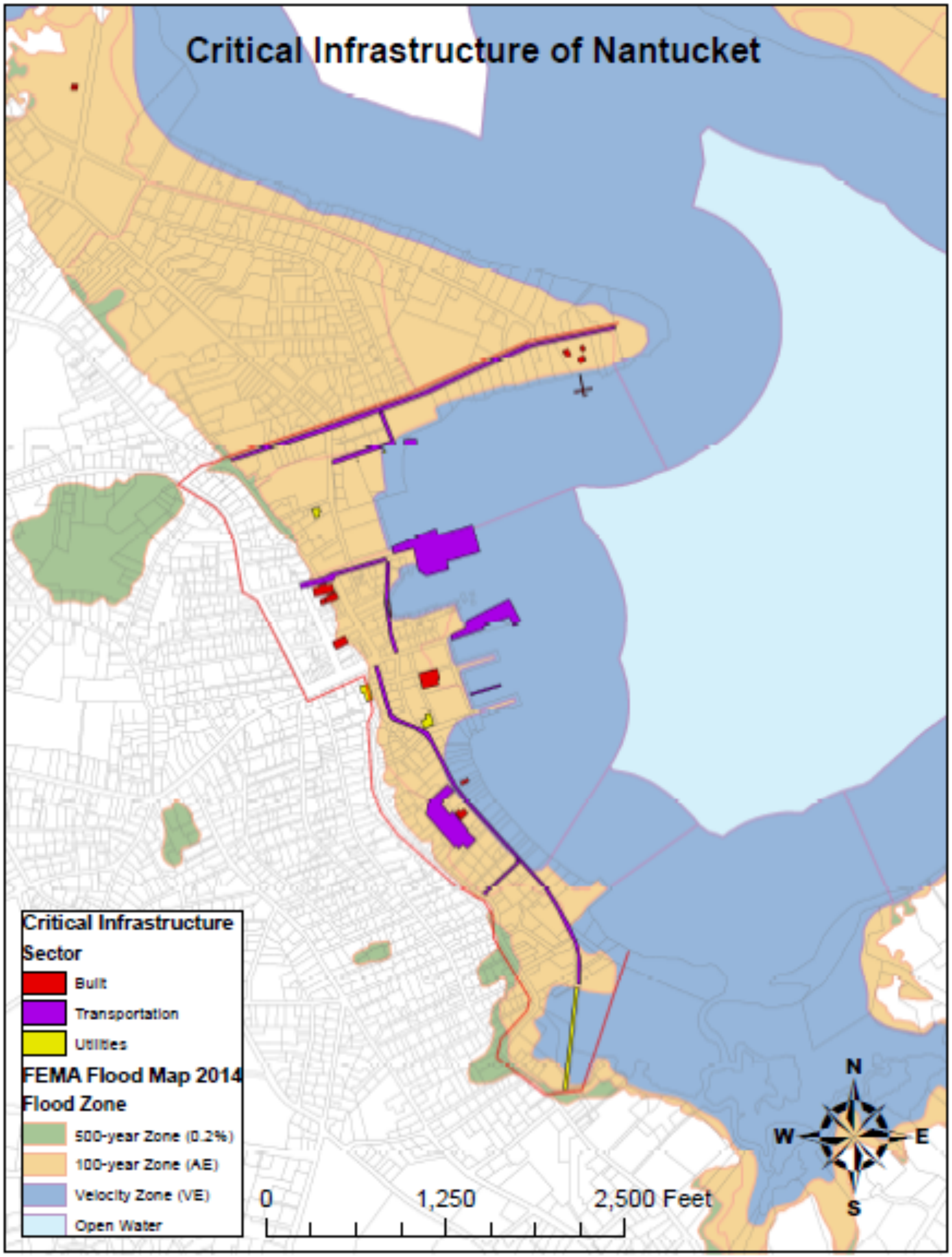

Figure 14: Map of Critical Infrastructure in GIS Layer

4.3 • Descriptions & Rankings of Infrastructure

Based on the information acquired, we have prepared summaries for each piece of infrastructure. These summaries are meant to give the reader a holistic understanding of each piece of infrastructure, including its key and unique attributes, and associated risk of storm surge damage. We begin each summary by noting the infrastructure sector, type, address, FEMA flood zone, important elevations, and assigned risk ranking. The elevations that are listed in this section—and in this report as a whole—are all in reference to the NAVD88 system. The elevations of all utilities, transportation, and built infrastructure are displayed as the surveyed heights rather than GIS heights, excluding the roads, which were not surveyed, and were interpreted using the GIS topography maps. We then go into more depth by describing the infrastructure and its most important features related to storm surge and its resiliency to withstand the effects of severe storms. Given the unique nature of each piece of infrastructure, each description highlights different key aspects that are important in the discussion of storm surge damages.

We have also given each piece of infrastructure a letter and number rank, in accordance with Table 3, and have explained why it was given this ranking. While we followed the guidelines shown in Appendix C during our assessment process, the risk rankings are illustrative rather than definitive. More precise assessment by structural engineers and other experts would be required to give more definitive risk ratings based on the likelihood of failure under different conditions and the extent and duration of the impacts. Table 5 summarizes the risk of all pieces of critical infrastructure in the downtown. We have determined there are 7 high, 11 medium, 6 low, and 2 very low at-risk pieces of infrastructure.

Table 5: Ranking of Critical Infrastructure

Likelihood	Consequence				
	1. Catastrophic	**2. Major**	**3. Moderate**	**4. Minor**	**5. Insignificant**
A. Very Likely	• Sea Street Pump Station			• Easy Street Bulkhead	
B. Likely	• Candle Street Substation		• Finance Dept. • Marine Dept./ Harbormaster's Office • U.S. Coast Guard Station	• Children's Beach Stormwater Pump Station	
C. Medium		• Easy Street • Stop & Shop	• Straight Wharf (Hy-Line) • Washington Street	• Children's Beach Boat Ramp • Sheriff's Office • Tanker Dock	
D. Unlikely		• Steamboat Wharf	• Easton Street • Goose Pond Sewer Main • Harbor View Way • Lower Broad Street • Town Parking Lot	• Francis Street • Natural Resources Dept. • Post Office	
E. Very Unlikely		• Union Street Telephone Building		• Town Administrative Building	• NRTA/ Health Dept.

The summaries below are shown in the order of the database, listed above in Table 4.

CANDLE STREET SUBSTATION

Sector	Type	Address	Zone	Elevation	Critical Elevation	Rank
Utilities	Electric Substation	6 Candle Street	100-Year Flood	3.8 feet	8.6 feet	1B

DESCRIPTION

The Candle Street Substation is located on the corner of Commercial Street and Candle Street. There is a gate to get inside the premises where two transformers are located just to the east of the building. The transformers are sealed sufficiently to prevent water damage. On the north side of the building are more transformers that are completely gated off on all sides to prevent any physical damage from floating or airborne debris in the event of a storm. These gated-off transformers are also elevated compared to the surrounding ground and can withstand 2 feet of water before any damage occurs. According to Dave Fredericks, energy projects consultant and retired employee of National Grid, the most frequent damage that occurs to energy infrastructure during storms is not due to water, but is instead physical damage from debris.

ASSESSMENT RATIONALE

Since this substation is the central hub for electrical distribution to the island, it is one of the most important facilities in the downtown area. If the substation were inoperable, there would be catastrophic (1) consequences, as the whole island would be without power, potentially for an extended period of time. National Grid would have to come to the island and make repairs if it was damaged and rendered inoperable. During most large storms, National Grid sends repair trucks to the island before the storm makes landfall in order to be proactive and make repairs as quickly as possible, since they are at mercy of the schedule of the Steamship Authority ferries. The substation is likely (B) to be flooded in a 100-year flood, as there will be approximately 6 feet of water surrounding the building. There are transformers that can be under 2 feet of water before being damaged. These are slightly elevated and partly surrounded by a concrete wall, as well as metal bars, to protect them from debris. Inside the building, there is electrical equipment that can maintain functionality in up to 1 foot of water before becoming inoperable. Physical damage is typically more of a concern than water damage. Smaller transformers outside will be underwater, but those are less critical for performing town-wide operations.

SEA STREET PUMPING STATION

Sector	Type	Address	Zone	Elevation	Critical Elevation	Rank
Utilities	Sewage Pump Station	1 Sea Street	100-Year Flood	4.7 feet	5.4 feet	1A

DESCRIPTION

The Sea Street Pump Station collects wastewater from the downtown area and pumps it to the island's Wastewater Treatment Plant; it is therefore the most critical pump on the island. The pump station is entirely in the 100-year flood zone, and is therefore subject to flooding, especially in the lower level pump and pipe gallery, which sits more than 10 feet below sea level. For flood protection, door dams and sandbags are deployed to slow and potentially stop an influx of water. The building is slightly elevated from the street, although this would make little difference in a 100-year flood. The station has a standby diesel generator, which can run for up to 500 hours in case of an emergency. However, if the pump station were to be inoperable, there would be a 1-hour buffer period before the manholes would overflow, resulting in raw sewage flowing into the streets.

ASSESSMENT RATIONALE

We have determined that if the Sea Street Pump Station were to be inoperable, there would be catastrophic (1) consequences. After an hour of inoperability, raw sewage would back up, and would therefore cause sewer overflows into the downtown area and into the harbor from street runoff, causing an incredibly unsanitary and potentially fatal situation for both the residents of the downtown area and the marine life in the harbor. Although a situation like this is less likely to happen because of the on-site backup generator, in a 100-year flood the generator would be submerged, which could lead to total failure. We have determined that it is very likely (A) there will be damage due to flooding. The building has flooded in the past, and although the pumps have worked underwater in the past, it was an anomaly and these should not be expected to work underwater in the future.

CHILDREN'S BEACH STORMWATER PUMPING STATION

Sector	Type	Address	Zone	Elevation	Critical Elevation	Rank
Utilities	Stormwater Pumping Station	15 Harbor View Way	Velocity Zone	3.0 feet (pump) 4.57 feet (control box)	5.97 feet (control box)	4B

DESCRIPTION

The stormwater pump station is located directly behind Children's Beach on Harbor View Way. Its purpose is to pump stormwater out of inundated areas. It is surrounded on all sides by wooden planks, and is constructed of concrete in the center. On the top exterior, there is an electrical box cover, an access door, a drain cover, and two pump caps. There is a bulkhead running along the beach up to the pump station, which protects the street from flooding, but does not necessarily protect the pump station from flooding. This pump station has eliminated a good amount of flooding from the Brant Point area, which used to flood extensively. The pump station itself is built to be submerged. An electrical control box about 180 feet from the pump, away from the ocean, controls the pump station. The critical elevation of this electrical box is about 1.5 feet off of the ground, and since the elevation at the base of the box is 4.57 feet, the critical elevation of the electrical box is approximately 5.97 feet. The greatest downfalls of this pumping station are the outlets into the ocean. Located further down the coast, these outlets are open to the ocean and, due to high tides or storm surge, can get inundated due to backflow in the pipes. The pump is not pressure-based and is only used to elevate the inbound water, as the system is gravity-based. Because of this, the pump does not provide enough pressure to overcome the opposing force of the ocean's tides and therefore is rendered relatively useless when the outlets are blocked; only when the ocean recedes can the pump extract the stormwater from inundated areas on land and relieve flooding in the downtown area.

ASSESSMENT RATIONALE

We have determined that if the stormwater pump station were to be damaged to the point of inoperability, it would have a minor (4) consequence. Since the pump station feeds a gravity-based pipe, it can only be effective after the storm when the water recedes below the outlet height. In addition, it is a relatively new piece of infrastructure (built in early 2000's), and only eliminates the inconvenience of leftover water in the Brant Point area. We have determined that, in a 100-year storm, the electrical box that controls the pump station would likely (B) get damaged. The lowest critical components in this control box would be under about 4 feet of water in a 100-year storm scenario.

GOOSE POND SEWER MAIN

Sector	Type	Address	Zone	Elevation	Rank
Utilities	Sewer Main	Under Goose Pond Trail	Velocity Zone	7.25 feet	3D

DESCRIPTION

Under the Goose Pond Trail at the end of Washington Street lies a cast iron, gravity-based sewer main that was built in 1980. This sewer main is connected with the Sea Street Pumping Station. It is responsible for the flow of sewage from the Washington Street and Orange Street areas, and has the potential to cause disruption to residents in these neighborhoods. In the event of the sewer main not working, the Wastewater Treatment Plant would be responsible for rerouting the sewage so it can get to the Sea Street Pump Station. Toward the harbor, there is a wetland that often gets flooded during storms and is 4-5 feet lower than the ground directly above the sewer main. Since this infrastructure is in the velocity zone, the surrounding ground is subject to erosion and floating debris that could cause physical damage. We have not labeled a specific height for the critical elevation, as the elevation of water will likely not determine the extent of damage to the earth berm under which the pipe runs.

ASSESSMENT RATIONALE

We determined the Goose Pond Sewer Main to be of moderate (3) consequence if it were to become disabled. If it were to become damaged, it is likely that the pipe wall would be compromised, spilling raw sewage into the surrounding area. This sewage could travel through the adjacent marshes on to the harbor. The consequence is not higher because this sewer main services a relatively small number of residences; the amount of disrupted or escaped waste would be manageable without a long disruption of service. The likelihood of the sewer main being damaged is unlikely (D). The main is protected by a very large earthen berm, which would take a while to erode; wave action damage would decrease once the main is fully submerged. Even if the mound eroded away, the iron piping would be very difficult to damage. There is not currently any visible damage to the surrounding ground and there have been minimal issues associated with this area in the past.

UNION STREET TELEPHONE BUILDING

Sector	Type	Address	Zone	Elevation	Critical Elevation	Rank
Utilities	Telecommunications	3 Union Street	100-Year Flood	8.24 feet	12-13 feet	2E

DESCRIPTION

This building is located at the base of the hill in front of Orange Street. It serves as the main relay station between the undersea cables and the cell towers. Telecommunication lines separate from the cables from the Candle Street Substation and travel underground to this building. Underground cables leave the building and travel to cell towers located elsewhere on the island. Inside the building, there are two main servers that process the information coming in and going out. The building has an elevated base floor of 10.04 feet, and the servers are also elevated within the building approximately 2-3 feet high.

ASSESSMENT RATIONALE

We have determined that if this building were to be inoperable, it would have a major (2) consequence, as all telecommunications services for the entire island flow through this building. If this building were to be inoperable in a severe storm scenario, it would hinder the effectiveness of emergency crews attempting to address the associated issues with the storm. This building, however, is very unlikely (E) to get flooded. Only the front of the building is in the flood zone, and the critical elevation is higher than the base flood elevation.

U.S. COAST GUARD STATION

Sector	Type	Address	Zone	Elevation	Base Floor Elevation	Rank
Built Infrastructure	Federal	10 Easton Street	100-Year Flood	4.42 feet	9.42 feet	3B

DESCRIPTION

The U.S. Coast Guard Station is located at the north end of the downtown harbor. The U.S. Coast Guard is responsible for ensuring marine safety during storms and therefore needs its boats and docks to be functional at all times. The premises consist of the main administrative building, a building for berthing and communications, and an engineering garage. To maintain its functionality, the U.S. Coast Guard staff needs to have full access to their communications room, which is located on the third floor of the building closest to the harbor, as well as to their boats. Communications are extremely important for the U.S. Coast Guard Station, because staff must keep in contact with the town's officials during a storm. They make sure that their boats are completely filled with fuel at all times, and have a backup storage tank in case of an emergency. The docks are frequently damaged by wave action and are often in need of repairs. The base floor elevation of the main administrative building is 9.42 feet and the ground height outside of this door is 4.42 feet. We have decided to call the critical elevation of this facility to be 4.42 feet, since water will be able to first enter the basements when the water level has breached the height of the stairs to the basements. The docks are also approximately this height as well and have a similar likelihood of being damaged by wave action.

ASSESSMENT RATIONALE

If the U.S. Coast Guard were to be hit by a 100-year storm surge, the electrical equipment would likely be damaged and power would be lost. While the U.S. Coast Guard has a backup generator, this power generation is only a temporary solution, as it is limited by the emergency on-site fuel supply. In the event of a long-term power loss, the communications room may be inoperable, which poses a concern for the safety of the island and of marine operations. During storms, the docks that the U.S. Coast Guard uses to get to its boats have the potential of being damaged as well, and if inoperable, there is no easy way of boarding these vessels. However, Nantucket is close enough to the mainland that if the U.S. Coast Guard were debilitated, other coastal towns on the mainland could help, which validates the U.S. Coast Guard as having a moderate (3) consequence if inoperable. During a 100-year storm, it would be likely (B) that the U.S. Coast Guard will have damages that pose a threat to maintaining its operations. It is in a low-lying area that is right next to the harbor and has had an extensive history of water damage. The main administrative building has a basement with electrical equipment and documents that are susceptible to flooding 2-3 times per year. During the No Name Storm of 1991, which had a water level more than two feet below the current 100-year base flood elevation, there was 38 inches of water in the basement. The average damages due to flooding per year are approximately $75,000, most of which is damage to electrical equipment in the basement.

TOWN ADMINISTRATIVE BUILDING

Sector	Type	Address	Zone	Elevation	Base Floor Elevation	Rank
Built Infrastructure	Municipal	16 Broad Street	100-Year Flood	8.09 feet	10.88 feet	4E

DESCRIPTION

The Town Administrative Building is in the center of town, situated next to the Sheriff's Office. This building contains administrative workers and files that are important to the Town of Nantucket. It also contains the only court in Nantucket; therefore, it is a highly important part of the piece of infrastructure that is used regularly. It has been known to flood in the back of the building, where the access point at ground level is on the same level as the base floor; in the front of the building, the base floor is 2.5 feet above ground level, approximately 10.88 feet above sea level. In the boiler room, the boiler was recently replaced due to damage by flooding, and the electrical components were raised on the walls. Computers are also raised 3 feet on desks, and would be well above the water level.

ASSESSMENT RATIONALE

The Town Administrative Building becoming inoperable would have a minor (4) consequence. During powerful storms, the functions of some town offices are moved elsewhere outside of the flood zone. If the building became inoperable, town functions could still be carried out at other locations, reducing the reliance on the building. Even with critical functions relocated, damage to the building could result in the loss of files. We ranked the building as having a very unlikely (E) chance of being damaged. The base floor elevation is approximately 1 foot over the 100-year flood elevation, so a 100-year storm would not even wet the floor. The amount of water needed to cause damage would be a water level closer to that of a 500-year flood, greatly reducing the likelihood that this damage would occur.

SHERIFF'S OFFICE

Sector	Type	Address	Zone	Elevation	Base Floor Elevation	Rank
Built Infrastructure	Municipal	20 South Water Street	100-Year Flood	9.29 feet	9.29 feet	4C

DESCRIPTION

The Sheriff's Office houses the county sheriff and his staff. This building is also a place for downtown officers to go during the day when they are in the downtown area. Prisoners are also held here in cells when waiting to go to court. This building has entrances that are at ground level, with a base floor elevation of 9.29 feet above sea level. Water has the ability to enter through doorways easily from East Chestnut Street, as well as through the garage doors. The front desk is elevated approximately 1 foot from the base floor, and does not get affected by water during typical flooding events. Yet, the front room dips down and is prone to flooding. The back of the building is where the majority of flooding occurs, when groundwater is forced up through the concrete floor by atmospheric pressure. In this part of the building, the main electrical components are raised 3 feet on the walls and the emergency generator is on cinder blocks. There is a sump pump, but it is only partially effective.

ASSESSMENT RATIONALE

We ranked the Sheriff's Office as having minor (4) consequence if deemed inoperable. During a major storm, the critical function of the station can be moved to a safer location. The employees housed in this building can continue daily operations elsewhere. The jail cells would become flooded, but prisoners could be moved to cells at 4 Fairgrounds Road. We found that the station has a medium (C) likelihood of being damaged. The station is built on a slab, on grade with ground level. The front of the building would see a few inches of flooding in a 100-year storm, but there are not many critical components to damage within the water's reach.

NRTA / HEALTH DEPARTMENT BUILDING

Sector	Type	Address	Zone	Elevation	Critical Elevation	Rank
Built Infrastructure	Municipal	3 East Chestnut Street	500-Year Flood	13 feet	13.57 feet	5E

DESCRIPTION

This building is split in half. The front half is the NRTA, which allows the public to obtain information about the different public transportations systems that the island offers. The Health Department is located in the back half of the building. The Health Department does local inspections of buildings to see if they are in good functioning condition. This building is located at the top of a hill, and is not likely to flood; the only water damage that has been seen in the past was from water flow down the street. The base floor elevation for this building is 13.57 feet, and is the main access point for water to potentially get inside the building.

ASSESSMENT RATIONALE

The NRTA / Health Department building mainly contains administration that will not cause a large environmental, health, or financial loss if inoperable, and therefore has been deemed insignificant (5). This building is located roughly 13 feet above sea level and is very unlikely (E) to be damaged in a 100-year flood, as the water level will be a couple of feet below this elevation.

EASY STREET BULKHEAD

Sector	Type	Location	Zone	Elevation	Rank
Built Infrastructure	Bulkhead	Easy Street	Velocity Zone	4.5 feet	4A

DESCRIPTION

The Easy Street Bulkhead is located on Easy Street, between Steamboat Wharf and Straight Wharf. It holds back the land on Easy Street, while also preventing excess damage due to wave action. However, it does not block the street from flooding due to storm surge. There is a large amount of rust on the top of the bulkhead, along with major deterioration, including rotting wood. The base of the bulkhead is made entirely out of wood. Although the average life expectancy of a bulkhead is 25-30 years, the Easy Street Bulkhead is roughly 70 years old. The only portion that has been renovated is the metal cap, which has been replaced several times. While there is no specific critical elevation for this piece of infrastructure, it is most likely to get damage when the water level is above 4.5 feet.

ASSESSMENT RATIONALE

Since the bulkhead stops wave action but doesn't prevent flooding, we ranked the bulkhead as having a minor (4) consequence if inoperable. The bulkhead prevents shoreline erosion and protects the critical transportation route to the Steamship Authority from wave action. This piece of infrastructure is very likely (A) to get damaged, because not only is it currently rusting and rotting away due to salt water damage and past storms, but it will also continue to get worse with the increasing frequency and severity of storms due to global climate change.

STOP & SHOP

Sector	Type	Address	Zone	Elevation	Base Floor Elevation	Rank
Built Infrastructure	Grocery Store	9 Salem Street	100-Year Flood	5 feet	5 feet	2C

DESCRIPTION

Stop & Shop is located on Salem Street, 150 feet inland from Old South Wharf. It is the major food provider for the downtown area. To the north is a parking lot, which sits lower than the store and, in the event of flooding, can collect water while the store itself remains unaffected. If the flood level was to reach the store, however, there are channels on either side of each door in which a door dam can sit to block some of the water; sandbags can also be placed in front of the doors to minimize flooding damage. Both the store and the parking lot are elevated above the wharf and the adjacent bulkhead. To its east is an enclosed fuel and gas storage area, which provides some protection from flooding and wave action, as its walls are nearly 6 feet tall. The generator that powers Stop & Shop is elevated out of the floodplain, so power generation during a severe storm is not often an issue. We have determined the critical elevation to be the elevation of the entrance, since potential problems could occur once water gets into the store through these doorways.

ASSESSMENT RATIONALE

Not being able to access Stop & Shop would be a major (2) problem, because it is the main source of food in the downtown area. While the downtown Stop & Shop is just one of the two Stop & Shop stores on the island, if it were inoperable, there would be more strain on the other Stop & Shop to provide food for the island. We have determined that Stop & Shop has a medium (C) likelihood of getting damaged due to storm surge and flooding. It is well constructed on a slab, and is located in an elevated area (compared to the depressed parking lot and adjacent areas around it). Also, the door dams and sandbags provide additional protection. In addition, the gas tank storage area protects the store from wave action.

MARINE DEPARTMENT / HARBORMASTER BUIILDING

Sector	Type	Address	Zone	Elevation	Base Floor Elevation	Rank
Built Infrastructure	Municipal	34 Washington Street	Velocity Zone	5.2 feet	5.2 feet	3B

DESCRIPTION

The Marine Department / Harbormaster's Office is located adjacent to the harbor, roughly at the same elevation as the docks. Doors are located at the back of the building facing the harbor and on the north side of the building. There are protective measures in place: drains are outside the doors, all internal wiring in the building is from the top to the bottom, and the outlets are raised 3 feet on the wall. Outside, electrical panels are raised 4 feet, which feed to the two docks and the building. There is a power panel at the beginning of the dock, which is raised 3 feet and is built with hurricane bracings. The base floor elevation of this building is 5.2 feet, the same height as the land outside. Once the water level reaches 8.2 feet, there is potential for electrical equipment damage to occur. The harbormaster is responsible for enforcing Massachusetts state boating laws and managing and inspecting harbor docks and moorings. They are the policing and rescue force responsible for protecting the harbor and up to 3 miles offshore of the island coastline. The first floor of the building contains a workspace and the communication systems. The second floor houses the office space and files for the harbormaster.

ASSESSMENT RATIONALE

The Marine Department / Harbormaster's Office are near the harbor, and thus have potential of getting flooded very frequently and are subject to wave action in major storms. However, the electrical system in the building is wired from the top down and all electrical outlets are 4 feet above the floor elevation. Outside electrical equipment is 3-4 feet above ground elevation as well. Nevertheless, during a 100-year storm these pieces of infrastructure would be submerged in water and have the potential to be damaged due to flood inundation. The communications systems would be damaged on the first floor, but critical files would be safe at higher ground. Additionally, the harbormaster function can be moved elsewhere outside of the flood zone during a storm, reducing risk. These factors equate to a moderate (3) consequence if the building were to be inoperable. Since the building is right on the shoreline and 5 feet below the floodplain of a 100-year storm, it is likely (B) that the building would be damaged. Wave action would play a large role in hitting the building and inundating the first floor.

FINANCE BUILDING

Sector	Type	Address	Zone	Elevation	Base Floor Elevation	Rank
Built Infrastructure	Municipal	37 Washington Street	100-Year Flood	4.99 feet	4.99 feet	3B

DESCRIPTION

This building contains all of the financial information, houses the functions that distribute paychecks to town workers, and writes checks to outside companies that provide equipment during storms. The parking lot behind the building is slightly elevated; therefore water tends to flow toward the back of the building. This building was recently given a new wood/plastic flooring, which prevents water from soaking into the floor and lets it flow through more easily in the case of a flood. However, the building was built on a slab and the main entrance on the front of the building is on grade at 4.99 feet above sea level.

ASSESSMENT RATIONALE

The Finance Department is critical because both the town and its residents need the ability to make financial transactions at all times, including during and immediately after a storm. There is potential for financial records and computer files to be destroyed during a large flood, which would result in a loss of irreplaceable data. There is a moderate (3) consequence associated with the Finance Department building being inoperable, since staff and computers could be relocated prior to a storm to maintain functionality. It is likely (B) to be damaged due to its location and building characteristics. In a major storm, there would be several feet of water surrounding, and inside, the building. The back of the building has also been known to flood easily due to rainwater runoff from the adjacent parking lot.

NATURAL RESOURCES DEPARTMENT

Sector	Type	Address	Zone	Elevation	Base Floor Elevation	Rank
Built Infrastructure	Municipal	2 Bathing Beach Road	100-Year Flood	6.66 feet	6.91 feet	4D

DESCRIPTION

The Natural Resources Department preserves, protects, and restores Nantucket's natural resources. It is located near Jetties Beach on Bathing Beach Road. Stormwater is mostly absorbed by the surrounding land and Jetties Beach. The front door is 15 inches from the ground, and the base of the building is 3 feet higher than the street. In the past, water has only reached the flagpole. If water were to reach the building, there are breakaway panels and a crawl space where the water can flow through, instead of damaging the building. The main issue during or after a storm would be being able to access the building, rather than the building actually flooding. Inside the building, all of the electrical equipment is raised 3 feet high on desks, and all of the files are sealed in the cabinets.

ASSESSMENT RATIONALE

While the Natural Resources Department plays an important role in taking care of Nantucket's natural resources, it is not necessary to be operational during or immediately after a storm. Therefore, we ranked it as a minor (4) consequence if the building were to become inoperable. The likelihood of the building getting damaged by flooding is unlikely (D), because the land where the building sits is elevated from the surrounding wetlands and the beach. There has not been any flooding in the past, but if there were a 100-year flood, the building would be under approximately 3 feet of water.

POST OFFICE

Sector	Type	Address	Zone	Elevation	Critical Elevation	Rank
Built Infrastructure	Federal	5 Federal Street	100-Year Flood	8.51 feet (back) 11.05 feet (front)	8.51 feet	4D

DESCRIPTION

The Post Office is located in the center of town, and is the main mail center in the downtown area. It contains many P.O. Boxes used by residents and local businesses. In a 100-year flood, the back where the garage is located would be flooded; therefore, mail would not be able to be distributed. There is a basement that leads to a storage area and a boiler room. In the basement, floodproofing tactics have been implemented in the past, but they have been known to be ineffective when there is a large amount of water. The base floor elevation for the Federal Street side of the building is 11.75 feet above sea level. We have considered the critical elevation for this structure to be where stormwater has the potential to flow down the staircase to the basement: 8.51 feet. It is important to note that groundwater typically comes up through the floor in the basement during floods, and a sump pump is used to minimize water levels.

ASSESSMENT RATIONALE

If the Post Office was inoperable and mail could not be delivered, there is potential for financial and legal problems to occur. However, there are other Post Offices on the island that are out of the flood zone, which would likely still be operable; therefore, the downtown Post Office would have only a minor (4) consequence if inoperable. The Post Office is located at the edge of the 100-year flood zone region and only has a minor region that will experience small amounts of water. All of the doors are elevated, and there are sufficient drains nearby that will assist in preventing water damage. It is unlikely (D) to get damaged during a 100-year storm.

CHILDREN'S BEACH BOAT RAMP

Sector	Type	Address	Zone	Elevation	Rank
Transportation	Boat Ramp	15 Harbor View Way	Velocity Zone	1.78 feet	4C

DESCRIPTION

The boat ramp is an extension of Harbor View Way and is the only boat ramp in the downtown area. It slopes into the water to provide land access for launching or retrieving small boats off of or onto a boat trailer. The road leading up to the ramp is constructed of the same asphalt concrete material that roads are commonly made of, while the ramp itself is constructed of metal planks sloping into the water. A design flaw in the ramp is that the metal planks are not steep enough—the ocean floor drops off too close to shore—which may create some inconvenient situations when the tides are very low. The ramp is made to withstand both inundation and wave action, so it is not seriously damaged when a severe storm hits. On either side of the ramp, there is a wooden dock, but they provide minimal added protection from wave action. There is also a wooden storm barrier on the street side of the boat ramp, which gets deployed to minimize wave action damage on Harbor View Way.

ASSESSMENT RATIONALE

We have determined that there would be a minor (4) consequence if the boat ramp were to be inoperable. Although it is the only boat ramp in the downtown area, most people remove their boats before a major storm; thus, the boat ramp is more critical before a severe storm, and less important after it would get damaged. We have also determined that in a 100-year storm, there would be a medium (C) likelihood of damage due to storm surge, since we have included the surrounding docks and storm barrier as part of this infrastructure. It is very unlikely that the boat ramp itself would get damaged, as it is constructed well and is built to withstand wave action of all magnitudes. However, the docks and storm barrier are made of wood, and are more likely to be damaged by the wave action of a severe storm.

STRAIGHT WHARF (HY-LINE)

Sector	Type	Address	Zone	Minimum Elevation	Rank
Transportation	Wharf / Ferry Terminal	34 Straight Wharf	Velocity Zone	3.63 feet	3C

DESCRIPTION

The Straight Wharf is primarily used for the Hy-Line Ferry to transport passengers to and from the island. In a major storm, the Hy-Line ferry typically docks in Hyannis to ensure the safety of its passengers and to minimize damage to the ferry. The wharf has experienced several incidents of flooding in the area, which also prevents the ship from operating. There are private boat slips at the end of the wharf, which have been torn apart in the past, and which were recently rebuilt to withstand fiercer wave action during severe storms. The height of the wharf is roughly 4 feet on the north side, while the metal ramps reach 5 feet above this height.

ASSESSMENT RATIONALE

We have determined that the Straight Wharf would have a moderate (3) consequence if inoperable, since the Hy-Line is primarily a passenger ferry and is not used to ship over supplies in bulk like the Steamship Authority ferries are. Since the top layer of the Hy-Line dock is built out of brick, which is a weaker material than concrete, it has a greater potential to be damaged by wave action; therefore it would have a medium (C) likelihood of being damaged by storm surge or wave action. The dock is also not as elevated as the Steamboat Wharf, so flooding is more likely to occur.

STEAMBOAT WHARF

Sector	Type	Address	Zone	Minimum Elevation	Rank
Transportation	Wharf / Ferry Terminal	1 Steamboat Wharf	Velocity Zone	5.16 feet	2D

DESCRIPTION

The Steamboat Wharf is located at the end of Broad Street in Nantucket Harbor. It houses the Steamship Authority ferry terminal, which includes both the fast ferry and the car/slow ferry. The sides of the wharf are made of metal and cement, and the top of the wharf is made of an asphalt concrete material. According to a worker at the Steamship Authority, the wharf floods with only a few inches of water due to wave action only, although Broad Street (the road leading onto the wharf), which sits at a lower elevation of 4-5 feet, gets flooded due to both storm surge and wave action. While the ramps at the wharf are considered critical, the ticket office in the center of the wharf is not considered critical.

ASSESSMENT RATIONALE

If the wharf were to be damaged and rendered inoperable, it would engender major (2) complications. The Steamship Authority is very important for the post-storm recovery process, as repair crews and equipment are brought to the island to repair the island's most critical functions. It is not catastrophic, since much of the anticipated equipment is brought to the island before a severe storm, and crews can fly into the island's airport, although it is a major disruption and can delay critical repairs for an inconvenient period of time. We have determined that the wharf would be unlikely (D) to get damaged by a 100-year storm. It is well protected and well constructed, with no history of damage in the past. However, the powerful wave action that would accompany a 100-year storm still has the possibility to damage the wharf.

TANKER DOCK

Sector	Type	Address	Zone	Elevation	Rank
Transportation	Dock	Between Old South Wharf and Commercial Wharf	Velocity Zone	6 feet	4C

DESCRIPTION

The Tanker Dock is located in between Old South Wharf and Commercial Wharf, on New Whale Street. It transports natural gas, home heating oil, and diesel through piping from the dock under New Whale Street to the fuel containers across the street about 6 times per year. There are currently minor amounts of rust on the connector pipes as a result of contact with ocean water. The pipes themselves are well sealed, so water has a minimal chance of getting inside. We have determined that there is no specific critical elevation for this structure, as the structure has potential to be damaged at any height of water, depending on the intensity of the wave action.

ASSESSMENT RATIONALE

The Tanker Dock would have only a minor (4) consequence if inoperable. The dock is only utilized a few times per year for the offloading of fuels, and is not a constant necessity. If fuel was eventually needed, they could be shipped to the island using semi-trailers on the transport ferry (which is how fuel is most often transported to the island). The dock itself would be the first part damaged due to wave action. If the transfer pipes were damaged, they could spill oil creating a health and environmental hazard. The amount of spillage is limited to the volume of the pipes, a reasonable amount to contain and clean, although this does not constitute an increase in consequence rating. We ranked the likelihood of damage to the docks as medium (C). We established the first part of the infrastructure to get damaged would likely be the wooden dock itself. The Tanker Dock is also susceptible to increased wave action, as the town docks were during winter storm Juno. It is not as likely to get as seriously damaged, however, because the Tanker Dock is shielded from wave action by the wharves on both sides, unlike the unsheltered town dock.

TOWN PARKING LOT

Sector	Type	Location	Zone	Elevation	Rank
Transportation	Parking Lot	Behind Finance Building	100-Year Flood	6 feet	3D

DESCRIPTION

The parking lot located behind the Finance Building at 37 Washington Street is the only public parking lot for the entire downtown area. During summer months, the downtown area is filled with tourists and this parking lot is completely overwhelmed. There are 175 parking spots, with 45 of these spots reserved for the town's marina, leaving 130 free for the public to park in, with an average turnaround time of 3-4 hours in the summer. In this parking lot, there are eight stormwater drains that are helpful in draining water when flooding is beginning to diminish. There is usually minimal damage to the parking lot itself due to storms, even though it is only 6 feet above sea level.

ASSESSMENT RATIONALE

If the parking lot were to be made inoperable for any extended period of time, there would be moderate (3) consequences, as it is the only public parking lot in the downtown area. It is unlikely (D) that the parking lot will be damaged by storm surge, as it is made up of pavement, which can easily withstand water. The main functionality of this infrastructure is for cars to be able to park, which would only be a problem during a large storm when there is water present. The eight drains in this lot are useful in draining water when the tides have receded, but do not work effectively during the storm and typically serve as a conduit for incoming flood waters. This, however, is not a large problem, as there will be a minimal number people needing to park there in any such severe event.

EASY STREET

Sector	Type	Zone	Elevation	Rank
Transportation	Road	Velocity Zone	4 feet	2C

DESCRIPTION

Easy Street is a road connecting Candle Street to Lower Broad Street. It is a single lane, one-way road that serves as the main artery for vehicles driving to the Steamship Authority ferry. The only other road connected to the Steamship Authority is Lower Broad Street, a one-way road leading away from the wharf. This makes Easy Street the only option for vehicles to arrive at the ferry (unless Lower Broad Street is made a two-way street in an emergency). Easy Street is also one of the only streets in the downtown with direct access to the waterfront. This makes it very susceptible to wave action and debris coming in from the harbor during a storm surge scenario, as it is located in close proximity to the harbor and it is only 4 feet above sea level. Along a portion of the road there is a bulkhead that serves to diminish wave action strength and provide support to the roadway.

ASSESSMENT RATIONALE

Easy Street is critical both before and after a storm because of its service to the Steamship Authority. All vehicles take this road to leave the island, including delivery trucks and utility vehicles. Throughout the duration of a severe storm, however, the road will have minimal use because the Steamship Authority will be closed, as will most of the downtown area. The stormwater typically drains when the tides recede to normal levels, making the road passable once again. If the road is flooded for extended periods, however, it greatly inhibits the ability of critical vehicles to do their job; nevertheless, alternate routes to the wharf could be established if necessary. Therefore, the roadway has a major (2) consequence if inoperable. During a storm, Easy Street is one of the first roads to flood because of its proximity to the water's edge. It is also one of the last roads to drain for the same reason. Out of all of the streets in our case study, Easy Street is the most likely to be damaged by storm surge. The street is roughly 4 feet above sea level and subject to wave action as previously mentioned. However, the road is made of concrete and is has a medium (C) likelihood of being damaged by storm surge and wave action.

HARBOR VIEW WAY

Sector	Type	Zone	Elevation	Rank
Transportation	Road	100-Year Flood	4 feet	3D

DESCRIPTION

Harbor View Way is a road that connects to Easton Street and to South Beach Street. It is in the shape of an "L." At the vertex of the "L" is the Children's Beach Boat Ramp. On the longer end of the road bordering the beach is the Children's Beach Pumping Station. During severe storms, the storm gate near the boat ramp on the edge of the road protects the road from damaging wave action, although it does not protect the road from flooding, as it runs approximately 4 feet above sea level. As with other roads, undermining due to water inundation can be an issue, although this road has a relatively low traffic volume, compared to other critical roads.

ASSESSMENT RATIONALE

This road leads to the only boat ramp in the downtown area, as well as to a major stormwater pumping station. Therefore, we decided that if it were to get damaged, it would have a moderate (3) consequence; it would disrupt the area for at least a few days, and would neither allow boats to be removed from the harbor for protection on land, nor provide maintenance access for the Children's Beach Stormwater Pump Station in the event the pump would be damaged. This road is unlikely (D) to be damaged by storm surge in a 100-year storm. While there will certainly be wave action and large amounts of water on the road in this situation, there will be a minimal chance of the waves doing any significant damage, as the water will be coming in and flowing down the street rather than making a strong direct impact. Any strong waves will be softened by the boat ramp at the end of Harbor View Way, as well as by the storm barrier that is put up at the end of the ramp before large storms.

EASTON STREET

Sector	Type	Zone	Elevation	Rank
Transportation	Road	100-Year Flood	2-6 feet	3D

DESCRIPTION

Easton Street is a primarily residential road that runs from the downtown out to Brant Point. It is one of the main roads that services the residences in the Brant Point area. Near the end of the road is a U.S. Coast Guard Station that is responsible for Nantucket and much of the surrounding waters. At the end of the roadway lies the Brant Point lighthouse, which provides boats safe access into the harbor. Easton Street lies at a fairly low elevation and is very susceptible to flooding, even during less severe storms, as it runs from 2-6 feet above sea level down the street. The roadway has poor drainage and collects water along the sides of the road after moderate rainstorms. The road readily floods during storms as storm surge breaks through from Brant Point as well as water entering in from Harbor View Way. Recently, 400 cubic yards of sand were added to the end of the road to mitigate the amount of water entering from Brant Point. During a major storm, the road quickly floods due to surge and limits the access to and from the U.S. Coast Guard station at the end of the road. The U.S. Coast Guard needs to transport servicemen and equipment to and from the station, with Easton Street being the only way to do that over land.

ASSESSMENT RATIONALE

Easton Street mainly services residential vehicles traveling to private homes; it also services the U.S. Coast Guard station at the end of the road. With transportation to the station necessary, the road would have a moderate (3) consequence if inoperable. The station is the only critical function reliant on Easton Street. If it were inoperable, the U.S. Coast Guard could find alternate ways to reach the station, but at a major inconvenience. The likelihood of this road getting damaged is unlikely (D), as it does not come in direct contact with major wave action. Damage at the end of the street is deflected by the sand dune at Brant Point and the road's waterside flank is protected by the row of houses on the waterfront.

LOWER BROAD STREET

Sector	Type	Zone	Elevation	Rank
Transportation	Road	100-Year Flood	4-6 feet	3D

DESCRIPTION

Lower Broad Street is classified as the intersection of South Water Street with Broad Street down to the Steamboat Wharf. This street is prone to flooding due to the low grade, where elevations vary from 4 to 6 feet above sea level; one part of the street dips down lower than the rest of the street, which makes it impassable when flooded. This is an issue, as it is the only way for trucks and cars to drive after leaving the ferry terminal, as Easy Street is a one-way road in the opposite direction. In extreme circumstances, the truck route may be needed to exit the terminal.

ASSESSMENT RATIONALE

If the street were impassable for an extended period of time during operable Steamship Authority hours, there would have to be a makeshift alternative route to allow for people to be able to leave the terminal. However, it is unlikely that the Steamship Authority will be operating during any storm that would cause this road to be impassable, giving it a moderate (3) consequence if inoperable. Lower Broad Street is protected by the Steamboat Wharf and has other physical barriers to minimize any wave action that might occur. There will be minimal undermining of the road during this event and flooding will reduce when the tide recedes. Therefore, it is unlikely (D) that this road will suffer damage that will cause it to become inoperable for an extended period of time.

WASHINGTON STREET

Sector	Type	Zone	Elevation	Rank
Transportation	Road	Velocity Zone	6 feet	3C

DESCRIPTION

Washington Street runs parallel to the harbor and is one of the primary streets that trucks use to get to the downtown from the rest of the island. It is relatively flat at 6 feet above sea level and covers approximately 85,000 square feet. It is a heavily used street by trucks and cars. Because it is in the velocity zone, it is subject to wave action and large amounts of stormwater during large storms.

ASSESSMENT RATIONALE

Washington Street is used as a truck route to get to and from the Steamboat Wharf. The consequence would be moderate (3) if impassable, because there would be no way to access the Finance Building, the Harbormaster's Office, or the Public Parking Lot, which are all classified as critical pieces of infrastructure. Since Washington Street is in the velocity zone and will be faced with wave action during strong storms, it is of medium (C) likelihood to be damaged.

FRANCIS STREET

Sector	Type	Zone	Elevation	Rank
Transportation	Road	100-Year Flood	6 feet	4D

DESCRIPTION

Francis Street is a one-way street that leads into Washington Street. During the summer, both trucks and residents heavily use this road. The top of Francis Street lies at approximately 8 feet above sea level while the bottom near the harbor is 6 feet above sea level.

ASSESSMENT RATIONALE

The critical function of Francis Street is to serve as a transport route for delivery vehicles. If the road were to become inoperable, alternate routes can be used to bypass and still reach the wharves; winter truck traffic is lower which makes this detour a feasible option. This ability to move the function leaves Francis Street as having a minor (4) consequence if inoperable. It is unlikely (D) that the roadway will become damaged. Wave action must first break the coastline and cross Washington Street, reducing the destructive force of the water. Francis Street lies parallel to the direction of wave action, reducing the chance of floodwater from undermining the roadway from its sides.

5 • Conclusions & Recommendations

In this chapter, we summarize our overall findings, provide recommendations for each piece of infrastructure, discuss our deliverables, and offer our suggestions for future work to guide the Town's efforts in preparing for the future.

5.1 • Conclusions

Nantucket has suffered substantial damage from storms in the past and is likely to suffer increasing damages in the future as the frequency and intensity of storms increase due to changing climate. In addition to rain and wind damage, storm surge is likely to cause substantial damage to critical infrastructure, including town assets, as well as private properties throughout the study area. The Town has spent considerable amounts of money in emergency planning and preparedness in the past, and will need to continue spending substantial amounts in the future. The Town and other entities must make the tradeoff between paying increased flood protection now versus the likelihood of extensive costs and losses associated with storms in the future.

The Town can draw upon a broad range of approaches found in Table 6 to safeguard specific pieces of critical infrastructure according to objective priorities, suggested in Table 7 below. These approaches include various modes of floodproofing, various tactics for elevating, and advance planning for relocating functions. Choices of mitigation will depend on likelihood of damage, extent and duration of consequences in the event of failure, and the cost and feasibility of mitigation choices. The tactic that is chosen for each piece of infrastructure varies depending on the specific infrastructure. Elevating infrastructure tends to be the most common mitigation tactic for the infrastructure in our boundary, as relocating the infrastructure may not be a viable option due to its location and function. Floodproofing tactics often supplement elevated structures. Any proposed mitigation tactics have the potential of taking several years to complete, and it is imperative that all planning committees take this into consideration.

5.2 • Recommendations

In this section, we will discuss our recommendations for the future based on our findings. We specifically recommend how to mitigate future damages to each structure and propose an order for which funding should be distributed to future projects. We have also provided general recommendations that will enhance and facilitate future project work and similar case studies.

The Town must address the long-term need to safeguard critical infrastructure as part of its capital planning.

- We recommend the Town and other entities (such as the Steamship Authority and National Grid) make long-term plans for protecting critical infrastructure as part of their ongoing capital planning processes.
- We recommend the Town and other entities follow the mitigation tactics and priorities described below.
- Regardless of this set of priorities, the Town and other entities should evaluate flood risks whenever they engage in major construction within the flood zone.

5.2.1 • Recommendations for Mitigation Tactics

We have provided our recommendations of how future damages could be prevented for each piece of infrastructure. In order to determine the best mitigation strategy, we took into account the nature of the infrastructure and its feasibility of relocation or modification. Given our team's limited expertise and the absence of readily available financial information, we have abstained from giving exact cost estimates for each proposed tactic. We have broken our recommendations into six different categories. Table 6 summarizes the specific recommendation we gave each piece of critical infrastructure. We recommend that all future structures be built to withstand a minimum of a 100-year flood without substantial damage.

Table 6: Recommendations for Hazard Mitigation

Recommendation	Infrastructure
Non-Relocatable Infrastructure: Elevate	Easy Street Bulkhead
	Candle Street Substation
	Sea Street Pump Station
	Steamboat Wharf
	Children's Beach Stormwater Pump Station
	Straight Wharf (Hy-Line)
	Tanker Dock
Non-Relocatable Infrastructure: Floodproof	Post Office
	Stop & Shop
Relocatable Infrastructure: Elevate	U.S. Coast Guard Station
	Marine Department / Harbormaster's Office
	Natural Resources Department
	Sheriff's Office
Relocation of Function	Finance Department
	Town Administrative Building
No Further Action	Children's Beach Boat Ramp
	Goose Pond Sewer Main
	NRTA / Health Department
	Union Street Telephone Building
	Town Parking Lot
Roads	Easton Street
	Easy Street
	Francis Street
	Harbor View Way
	Lower Broad Street
	Washington Street

Non-Relocatable Infrastructure: Elevate

Several of the pieces of infrastructure under the greatest threat are structures that cannot be moved from their current sites. Instead, their physical structures must be modified to mitigate further damages. The major pieces of infrastructure that fall into this category are listed below.

- The Sea Street Pump Station's best course of action is elevation. Relocation is not a feasible option because the Sea Street Pump Station has a well-structured sewer system feeding to that location. This structure is built out of brick with a basement; therefore the best elevation strategy is to extend the walls of the building, but construct the doors, window frames, and floor to a taller height. In addition, we suggest elevating the generator so it wouldn't be affected by water and implementing a sump pump as well.
- The Candle Street Substation needs to be further elevated. It cannot be relocated because both undersea energy cables are directed to that station and it would be more costly to redirect them if the building were to be moved. Since the building is constructed of brick, elevation should consist of wall extension by raising the height of doors and window frames along with a base floor constructed at the new elevation. We also suggest elevating the transformers and adding a sump pump.
- The Steamboat Wharf and Straight Wharf (Hy-Line) should be elevated in the future. The concrete and steel would also need to be reinforced. The walkways and ramps to access the boats should also be raised to account for rising sea levels. Both administrative buildings should be reinforced with wet floodproofing.
- The Tanker Dock should be elevated to adjust for rising sea levels and be reinforced with materials stronger than wood, such as steel.
- The Easy Street Bulkhead should be elevated to meet both rising sea levels and to mitigate a greater amount of wave action; it should be built of steel to be more rigid against these forces.
- The Children's Beach Stormwater Pump Station control panel should be elevated a few feet to rise above the floodplain.

Non-Relocatable Infrastructure: Floodproof

Another type of infrastructure encountered was one that is not movable, but also could not be elevated. In this case we suggest further floodproofing. We suggest substantial dry floodproofing for structures with vital or hard-to-replace components close to the ground. If water seepage is not as severe, wet floodproofing with door dams and sandbags are sufficient.

- Stop & Shop is a vital resource that cannot leave the downtown, but its construction on a concrete slab makes it too expensive to lift. On the exterior, well sealing door dams and sandbags should be implemented, while the backup generator could be elevated. For the interior, we suggest wet floodproofing to protect electrical and refrigeration systems.
- The Post Office also serves a prominent role in the downtown and should remain there. Only the rear garage is at risk, making dry floodproofing with the use of door dams and sandbags the easiest and most cost effective option.

Relocatable Infrastructure: Elevate

Some structures in the flood zone can be relocated, but relocation is not the best option. For these sites, elevation to the 100-year flood level is the recommended choice.

- The U.S. Coast Guard station is on useful property to serve its purpose and elevation will not reduce damages in the basement. Elevation would need to be to the 500-year flood level because it is a federal building.
- The Sheriff's Office has the ability to relocate if necessary, but its high ceilings allow for easy elevation by constructing a new base floor, such as the one already in place in the front office.
- The Natural Resources Department on Bathing Beach Road is a small building with a smaller floor plan; this increases the ease of simple elevation onto pilings and is a better option than trying to find a new location altogether.
- The Marine Department / Harbormaster's Office has the ability to relocate, but is best suited to be a waterfront office, making elevation the best option. Raising the entire structure over 5 feet to be above the floodplain will not likely happen. Instead, all critical functions should be moved to the second floor; the first floor should be left as a space for non-critical functions or storage, reducing the chance for substantial damage.

Relocation of Function

For infrastructure that would not be cost effective to raise or floodproof, relocation of function is the best course of action. Some town offices are in the floodplain but do not necessarily have to be in the downtown. These offices should be relocated out of the flood areas and moved to a safer area to eliminate unnecessary damage to town property. We recognize that relocating town offices is controversial. Alternative office space outside the flood zone may not be available and many stakeholders and citizens in general wish to keep town government functions and staff in the downtown area.

- The Finance Department building cannot be moved, but the function can be easily relocated out of the velocity zone on Washington Street. Staying in that building is not worth the cost of elevation or floodproofing.
- During a storm, the function of the Town Administrative Building should be temporarily relocated. Its base floor is located above the 100-year floodplain, and a major event closer to a 500-year flood would be needed to cause critical damage.

Roads

Using our operational definitions, it was difficult to categorize roadways effectively into the prioritized list. It is more unlikely for a road to become inoperable in the same sense that a building could be. In many cases the roadways would get fully submerged and possibly impassable, but would not be damaged enough by wave action to be considered inoperable. Because of their difficulty to be significantly damaged, we do not suggest any modifications at this time. What we do suggest is to plan for roadway elevation in the future. At some point, roads will be torn up for the purpose of repaving or access to utility lines; at this point roadways should be repaved to a slightly higher elevation. In the future, greater storm frequency will increase the number of times roads are impassible due to water depth. Although raising road heights by such a small amount will not make a difference in a 100-year flood, it will reduce the frequency of impassibility in less severe storms. Homes and buildings along these roads will eventually elevate to meet the rising floodplain elevations and will need roadways to meet their new heights, especially along Lower Broad Street and Easy Street.

No Further Action

The protection of certain pieces infrastructure is not worth the cost of doing so. Sometimes it is most cost effective to pay for damages after they occur, rather than paying for proactive mitigation tactics; this is considered "the price of doing business."

- The Union Street Telephone Building and the NRTA/Health Department Building lie outside of the 100-year flood zone, and a major event closer to a 500-year flood would be needed to cause critical damage.
- The Goose Pond Sewer Main is not at imminent risk of damage to the infrastructure.
- The Town Parking Lot and Children's Beach Boat Ramp are not critical during a storm and have minor consequences if damaged. Therefore, no further modifications are advised at this time.

5.2.2 • Recommended Priorities

Our team has determined a priority listing for which pieces of infrastructure are most crucial to work on first. This priority ranking system takes into consideration both the infrastructure's assigned rank and the proposed recommendations our team has given. Infrastructure that is highly likely to be damaged and will cause significant problems if inoperable has been given a high priority. However, if the mitigation tactics are costly and difficult to implement, the infrastructure may be given a lower priority than if the infrastructure could be protected quickly for a minimal cost. Table 7 shows our priority list.

This list is meant to give a general recommendation of the order in which pieces of infrastructure should be addressed. If the opportunity presents itself to work on one piece of infrastructure in a less expensive and timely fashion over another piece of infrastructure, we recommend that the owners seize the opportunity and begin working as soon as possible. The system we used for prioritizing infrastructure is open to modification. We recommend that the Town and other entities review our protocols and modify them as needed in the future.

Table 7: Priority List

Number	Rank	Infrastructure
1	1A	Sea Street Pump Station
2	1B	Candle Street Substation
3	2D	Steamboat Wharf
4	3B	Marine Department / Harbormaster's Office
5	3B	U.S. Coast Guard Station
6	4A	Easy Street Bulkhead
7	3B	Finance Department
8	2C	Stop & Shop
9	3C	Straight Wharf (Hy-Line)
10	4C	Sheriff's Office
11	4B	Children's Beach Stormwater Pump Station
12	3D	Goose Pond Sewer Main
13	4C	Children's Beach Boat Ramp
14	2C	Easy Street
15	3C	Washington Street
16	3D	Town Parking Lot
17	3D	Lower Broad Street
18	4C	Tanker Dock
19	3D	Harbor View Way
20	3D	Easton Street
21	4D	Francis Street
22	4D	Post Office
23	4D	Natural Resources Department
24	2E	Union Street Telephone Building
25	4E	Town Administrative Building
26	5E	NRTA / Health Department

5.2.3 • Other Recommendations

All property owners within flood zones should assess their risks by using appropriate data to determine future actions. Our team recommends that parties first look up the current FEMA flood maps and make note of where the desired piece of infrastructure is located within the flood zones. From there, they should compare it to the topography maps found on Nantucket's GIS to see if they are in a low-lying area that is prone to flooding. To get a more accurate value for the infrastructure's elevation, they should then hire a surveyor to get a reading of the infrastructure's base floor elevation along with the elevation of the corners of the building.

In order to determine the value of a piece of infrastructure, such as a building, the Assessor's website should consider having a separate value that includes the fixed assets of the building. This information was difficult to obtain given our time constraint, and therefore was not added to the value on the checklists.

With help from the Nantucket Planning Office, our project team was able to observe when infrastructure in our study area was last modified. However, the available documents did not provide the context of why the modifications were conducted. In order to better prepare for future projects, it would be beneficial if better records were kept on specific flood protection modifications to infrastructure to observe trends over time. Similarly, the Department of Public Works did not have sufficient records for when roads were last paved, and thus we recommend that these records be kept for future reference. It would also be very beneficial if records for previous storm damages to each piece of infrastructure would be made public for historical reference.

Certain inconsistencies in determining elevations arose during the course of our project. We discovered that the topography maps found on the Nantucket GIS do not correspond entirely with the surveyed heights, and in some cases, are even off by upwards of 2 feet. One solution is to recreate the topographical maps to be more accurate to the true height. In the practice of comparing sea levels to surveyed elevations, it is very important to make sure that all heights are with respect to the same reference point. We recommend that all parties use the North American Vertical Datum (NAVD88) as a reference in this line of research.

5.3 • Deliverables

We have provided an online summary database containing information about all pieces of critical infrastructure that is accessible for public perusal on the Town of Nantucket's website under the Emergency Management section (http://www.nantucket-ma.gov/335/Emergency-Management). In addition, there is also a hard copy of this database in the form of a binder that has been left with Dave Fronzuto at the Nantucket Emergency Management Agency. Each piece of infrastructure has a display of its summary, its checklist, and any important pictures. Within each infrastructure's summary, the name and ranking are color-coded, in accordance with the risk chart in Table 3. The summaries also include individual recommendations for each piece of infrastructure. We recommend that the town take into consideration these specific recommendations in addition to the previously mentioned general recommendations.

We have also created a GIS database using information from our checklists, as well as incorporating already existing layers from the Nantucket GIS such as flood zone, topography, and land parcels. Our original layer includes a map of the critical infrastructure in our study area, color-coded by sector type, as shown in Figure 14. The GIS will allow the viewer to see a comparison of flood zones and elevation for each piece of critical infrastructure. With this information, the reader can visually observe the extent of flooding that could occur at any given piece of critical infrastructure in a 100-year or 500-year storm. When clicking on a specific infrastructure for identification, a dialog box appears and displays the infrastructure name, sector, value, ground elevation, base floor elevation, risk value, FEMA flood zone, and page number in the summary database. Figure 15 shows the dialog box associated with the Candle Street Substation.

5.4 • Future Work

Due to the time constraint imposed on our research, we were only able to investigate the protection of critical infrastructure in the downtown area. Given more time, a future project group could repeat the evaluation of other items of critical infrastructure located in flood zones elsewhere on the island.

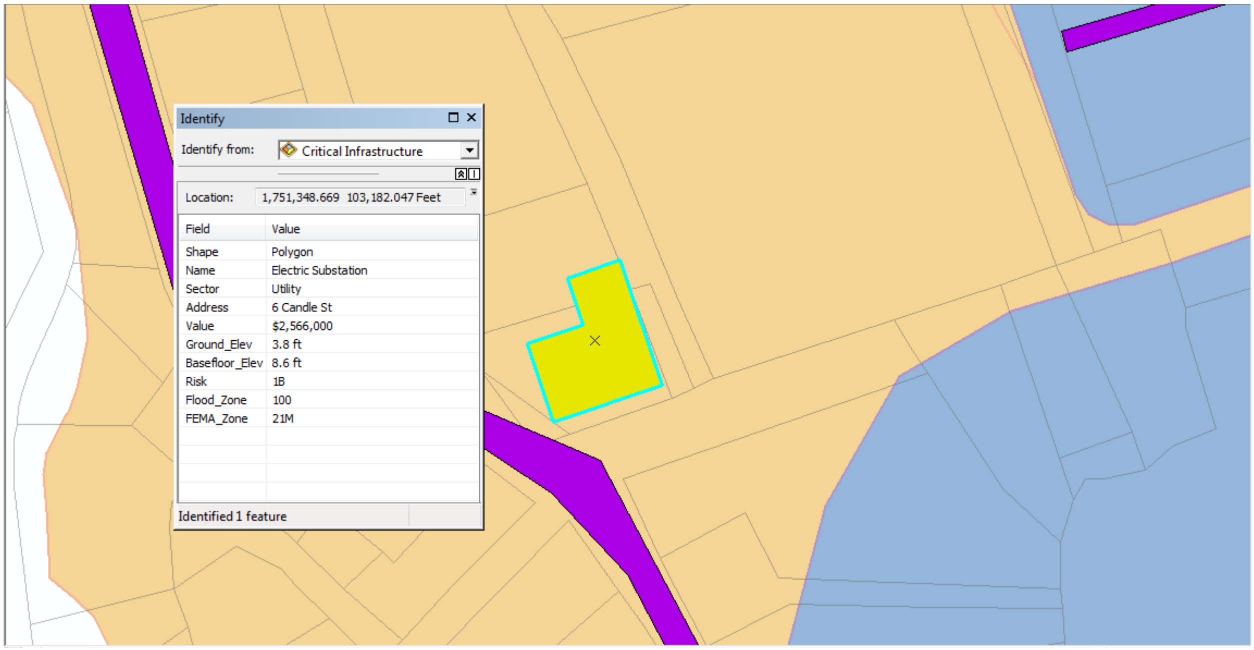

Figure 15: Information Found in the GIS Dialogue Box for the Candle Street Substation

Electrical power is essential for most operations; it would therefore be beneficial if future case studies encompassed the impacts of storm surge on all sensitive electrical equipment in the study area and beyond. This would include looking at transformers that are connected to the infrastructure of interest as well as all interior and exterior electrical equipment that the building needs to operate.

In order to conduct a more in-depth analysis of this project, we suggest that certified inspectors assess each of the highlighted pieces of infrastructure to get a more qualified opinion of the structural integrities. In accordance with this, we suggest that all pieces of infrastructure get an estimated mitigation cost.

In future variations of this project, it may be desirable that information checklists, such as those found in our summary database, contain the year last modified, dollar values for previous damage, and total value for each piece of infrastructure.

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Appendix A: Interviews

We are a group of students from Worcester Polytechnic Institute working in collaboration with the Nantucket Emergency Management Agency to mitigate issues associated with critical infrastructure that are caused by storm surge. We would like to ask you a few questions on current policies and practices regarding __________. The interview should take less than 30 minutes. Please know that you may skip any question you are not comfortable answering, and may also stop the interview for any reason. Since your views are important, we would like to quote you in our final report but we will give you the right to review any quotations we use prior to publication. We can make your contributions anonymous, however, if that is what you would prefer. May we proceed?

In addition to the following baseline questions, we often asked for relevant documents and sources that we could use for our report. Most questions often branched out into more specific topics relevant to the interviewee that are not present in these listed questions.

1. What is your expertise and responsibilities?
2. Can you please define the term "critical infrastructure" in your own words?
3. Would you consider these pieces of infrastructure to be critical and are there any you recommend we add or take off? (We would then show our most updated database of critical infrastructure)
4. When determining the condition of a piece of infrastructure, what are some guidelines that are followed?
5. Do you have any examples of previous damages that have occurred from major storms? (Juno and No Name Storm mainly)
6. What mitigation tactics, if any, are in place to protect infrastructure in our study area?
7. Are there any other people we should contact that would be useful in the context of this project?

A few specific recurring questions included:

1. What is this piece of infrastructure responsible for? How long can it be out of use before problems occur?
2. What types of problems are typical in this situation? How are they fixed?

Appendix B: Experts Interviewed

Name	Title	Date	Topics Discussed			
			Utilities	Built	Transportation	Other
Mike Burns	Transportation Planner	11/2/2015			✓	
Steve Butler	Building Commissioner	11/18/2015	✓			
Kara Buzanoski	Director of the Department of Public Works	10/30/2015	✓		✓	
Jeff Carlson	Natural Resource Coordinator	11/12/2015		✓		
Debbie Dilworth	Assessor	11/18/2015		✓		
Stephen Drabkin	Postmaster	12/3/2014		✓		
Dave Fredericks	Energy Projects Consultant & Former National Grid Regional VP	11/4/2015	✓			
Dave Fronzuto	Emergency Management Coordinator	10/26/2015 11/2/2015 11/6/2015 11/16/2015 11/18/2015 12/3/2015 12/7/2015	✓	✓	✓	✓
Brenda Garnett	Asst. Superintendent of Operations, County Sheriff's Office	11/18/2015		✓		
David Gray	Chief Operator at Wastewater Treatment Plant	11/5/2015 11/10/2015	✓			
Frank Holdgate	Surveyor	11/12/2015 12/1/2015	✓	✓	✓	
Steve Holdgate	Manager at National Grid	11/18/2015	✓			
Larry Kester	Facilities Manager	11/12/2015		✓		
Robin Lapiene	Accounting Clerk	11/18/2015		✓		
Peter Morrison	Demographer	10/26/2015 11/2/2015 11/16/2015 12/7/2015				✓
Nathan Porter	Nantucket GIS Coordinator	11/3/2015 12/3/2015				✓
Gregg Tivnan	Assistant Town Manager	11/6/2015		✓		
Mark Voigt	Historic District Commission Administrator	11/4/2015		✓		
Matthew Welsh	U.S. Coast Guard Brant Point Senior Chief	11/10/2015 11/12/2015		✓		

Appendix C: Risk Chart Consequence Factors
(ICF International, 2009)

Catastrophic

- Financial: Huge financial losses involving many people and/or corporations and/or local government; large long-term loss of services; permanent damage and/or loss of infrastructure service across sizeable regions; high financial loss and/or environmental remediation costs; long-term impact on commercial revenue.
- Health: Severe adverse human health with multiple events leading to disability or fatalities and requiring emergency response.
- Environmental: Permanent loss of environmental service.

Major

- Financial: Major financial losses for many individuals and/or a few corporations; some long-term impacts on services; some homes permanently lost; existing infrastructure damage or loss requiring extensive repair.
- Health: Permanent physical injury and fatalities from individual event.
- Environmental: Significant impairment of environmental service; some species loss.

Moderate

- Financial: High financial losses, probably for multiple owners; disruption of services for several days; widespread infrastructure damage and loss of service requiring maintenance and repair.
- Health: Adverse human health; most populations affected; people displaced from their homes for several weeks.
- Environmental: Impairment of environmental service; species affected.

Minor

- Financial: Moderate financial losses for small number of owners; disruption of services for a day or two; localized infrastructure damage.
- Health: Slight adverse human health affect; vulnerable populations affected.
- Environmental: Short duration and intensity of impairment to environmental service; minimal effect on species.

Insignificant

- Financial: No infrastructure damage; minimal financial losses; short-term inconvenience.
- Health: No adverse human health effect or complaint.
- Environmental: Minimal impact on environmental services.