3-2022

Natural Infrastructure Alternatives Mitigate Hurricane-Driven Flood Vulnerability: Application to Tyndall Air Force Base

Kiara L. Vance

Recommended Citation

Vance, Kiara L., "Natural Infrastructure Alternatives Mitigate Hurricane-Driven Flood Vulnerability: Application to Tyndall Air Force Base" (2022). *Theses and Dissertations*. 5426.
https://scholar.afit.edu/etd/5426

NATURAL INFRASTRUCTURE ALTERNATIVES MITIGATE HURRICANE-DRIVEN FLOOD VULNERABILITY: APPLICATION TO TYNDALL AIR FORCE BASE

THESIS

Kiara L. Vance, Captain, USAF

AFIT-ENV-MS-22-M-268

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT-ENV-MS-22-M-268

NATURAL INFRASTRUCTURE ALTERNATIVES MITIGATE HURRICANE-DRIVEN FLOOD VULNERABILITY
APPLICATION TO TYNDALL AIR FORCE BASE

THESIS

Presented to the Faculty

Department of Engineering Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

Kiara L. Vance

Captain, USAF

March 2021

DISTRIBUTION STATEMENT A.
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT-ENV-MS-22-M-268

NATURAL INFRASTRUCTURE ALTERNATIVES MITIGATE HURRICANE-DRIVEN FLOOD VULNERABILITY: APPLICATION TO TYNDALL AIR FORCE BASE

Kiara L. Vance

Captain, USAF

Committee Membership:

Lt Col Justin D. Delorit
Chair

Dr. Christopher M. Chini
Member

Dr. Tay W. Johannes
Member

AFIT-ENV-MS-22-M-268

Abstract

Hurricane frequency and magnitude intensification are expected over the remainder of the twenty-first century. However, uncertainty in future projections requires that coastal communities approach adaptation decisions with caution. Traditional or hard adaptation approaches are disruptive, costly, and inflexible, and are typically irreversible. Soft adaptations, like policy and management solutions, are largely unenforceable. When they are enforced, they have been overly prescriptive as viewed by communities that are not currently experiencing widespread coastal flooding or damage from intensified hurricanes. Hard, natural adaptations have emerged as an opportunity to partially or temporarily mitigate the growing risk of recurrent and extreme flooding, without the large capital investments required for traditional hard approaches, particularly where natural marine infrastructure like barrier islands, mangroves, and wetlands already exist. Despite growing popularity, most decision frameworks for natural adaptations have not leveraged intensification expectations for hurricane events, nor have they considered economic feasibility of risk reduction. This research uses multi-hazard damage evaluation software and spatial analysis, to investigate placement of dredged sediment as a barrier island maintenance technique to determine its economic viability, as compared with traditional engineering solutions such as stormwater system capacity expansion, seawalls, and breakwaters. The efficacy of this strategy is tested against 18 time- and intensification-calibrated threat scenarios, and is applied to existing barrier islands at Tyndall Air Force Base. The scenarios act as a range of investment opportunities and implementation guidance policies that are geared towards protection of the installation. They are intended to be partial measures that provide time for decisions to consider whether flooding realities are consistent with projections, and which, if any of the more invasive, hard adaptation strategies are appropriate given budget constraints.

The results illustrate that protection of Tyndall’s 7 square miles of existing barrier islands could help avert facility and infrastructure damage from high-intensity hurricane surge events predicted at 2100 by up to 3 orders of magnitude compared to a status quo scenario. Additionally, even minor island maintenance efforts at lower risk scenarios slows the impact of predicted flooding levels. The broader implications suggest that planners should look to preserve and buttress natural infrastructure that provides surge protection and wave attenuation based on its ability to mitigate damages from rising sea levels and the tradeoffs between damage avoided and maintenance costs.

For my Dad, the survivor, and my Mom, for her unwavering support

Acknowledgments

First, I would like to thank my partner for his dedication and encouragement though the challenges over this last year, and my family for the staunch support and love. I wouldn't be where I am today without you.

I would also like to send a colossal thank you to my advisor, for pushing me to better myself as a student, officer, and person, and helping me learn to trust my own capability.

Finally, thank you to the AFIT Faculty, for endless patience and thoughtful conversation that have shaped my time here.

Kiara Vance

List of Figures

List of Tables

NATURAL INFRASTRUCTURE ALTERNATIVES MITIGATE HURRICANE-DRIVEN FLOOD VULNERABILITY:
APPLICATION TO TYNDALL AIR FORCE BASE

Table of Contents

Page

I. Introduction

Extreme weather is likely to become more frequent and intense over the coming century as a result of climate changes to include warmer oceans, intensified hydrology, and rising global sea levels; ultimately this puts coastal communities at risk. (Fraza & Elsner, 2014, Fischer, et al 2021). As cities continue to develop waterfront property, there will be greater pressure to protect built assets from the increased recurrent and extreme-event drive flooding, using robust infrastructure (Dugan et al, 2011). Communities historically have had the opportunity to adjust to inundation and surge events in two ways: traditional built infrastructure that is robust, but brittle, and policy adaptions, which are soft and resilient, though both options present planners, engineers, and decision makers challenges (Woods, 2015). Hard, or built infrastructure solutions have benefits if certainty and risk are appropriately forecast. However, prediction uncertainties create planning problems for local, state, and national officials, given the long temporal threat horizons, i.e., decades and centuries, over which climate change is believed to influence coastal communities. Factors that traditionally impact the intensity of extreme weather events, e.g., mean sea surface temperature, sea level, and tide conditions, have been shown have an exceedance probability growth of roughly 40% by 2100 (Kossin, 2020). The scales of probabilistic and magnitude change in extreme events create a demand signal for adaptative coastal communities, which drives discussions that center on the protection of existing public and private infrastructure assets.

While traditional engineering solutions are effective in flood prevention, they are time intensive, cost prohibitive, and difficult to repair after damaging events. They are also brittle, in that once overcome, they are of no value or in some cases, compound or exacerbate damage and suffering. For example, levee failures and elevation deficiencies in New Orleans during Hurricane Katrina resulted in prolonged overtopping and surge inundation which would have been brief if constructed properly (Van Heerden et al, 2007). Structures like seawalls and breakwaters are damaging to local ecology, which further disrupts coastal environmental communities (Morris et al, 2017). In addition, protective coastal infrastructure is difficult to design given the uncertainty surrounding environmental predictions that drive design, and uncertainty within assumed risk determines the success of the selected response mechanism. The natural reaction is to overbuild infrastructure, or design with large factors of safety. The risk of this approach is that overbuilt infrastructure may never be challenged near its design capacity, which is considered an excess in the public eye. The alternative—underbuilt infrastructure—has clear disadvantages. The vast majority of communities have difficulty adapting to increased risk dynamics (Baldwin 2021).

Communities may not have to invest heavily in sunk cost-based protection against a projected, but uncertain future events. Traditional structural controls can and do work well, until the design criteria are overwhelmed; for example, a seawall at a certain height will be effective until a wave event surpasses the design elevation. Alternative solutions with option value provide an opportunity to leverage lower cost investments, e.g., beach restoration, such that the public can invest incrementally in lower cost protection intervention, which enables decision makers to take a “wait and see” approach before making sunk cost investment decisions (Contento et al, 2019).

Soft adaptations, such as policy and regulatory improvements, are interventions that require little capital, as compared to hard adaptations, and high levels of implementation and enforcement knowledge and authority. However, soft adaptations are generally believed to have decreased certainty of protection due to localized, highly variable measures, and difficulty in management and control of implementation across large geographic areas (Wagner et al, 2014). For example, increased regulation on coastal development has strong socioeconomic impact, particularly where local government revenues are based on waterfront property taxes (Shi et al, 2018). These same regulations have the potential to create climate slums, where communities are consistently devastated by climate change, because they lack the fiscal resources to withstand losses (Ajibade, 2014; World Economic and Social Survey, 2016). Another drawback associated with policy enforcement is developer withdrawal, which forces abandonment of coastal housing projects. This course of action is politically and socioeconomically unpalatable, and could lead to regret in terms of needlessly abandoned or undeveloped high-value real estate, if predictions never come to pass. Additionally, soft adaptation measures typically have large overlap with other physical alternatives.

Ecologically focused solutions, like marshes, wetlands, reefs, and dunes, can be used to defer or eliminate the need to invest in expensive, and potentially ecologically destructive engineering measures for coastal protection. However, these practices lack extensive, large-scale studies of application. Previous studies have proven natural infrastructure efficacy against Category 1 storm damage and surge flooding; specifically, marshes with and without sills protected estuarine shorelines from erosion better than bulkheads during Hurricane Irene (Gittman, 2015). Other research revealed that damage to existing vegetation and structures was recovered within 13 months (Gittman et al, 2014). This timeline, and resilience, cannot be matched by traditional engineering solutions with respect to funding and execution. Moreover, natural infrastructure, like the alternatives mentioned above, minimize coastal flooding, with a cost-to-benefit ratio that is nearly seven-to-one in the Gulf Coast (Reguero et al, 2018). U.S. Coastal Wetlands provide an estimated $23.2 billion in protection from damage every year, but have not been proven to be competitive with built adaptations or be effective long-term against higher intensity flood events that are predicted over the next hundred years.

Despite the significant contributions of the aforementioned studies, a framework must be developed to enable engineers, ecologists, and community planners to investigate the tradeoffs between hard, soft, and adaptive infrastructure alternatives to achieve protective aids and evaluate risk to proposed benefits. This study aims to resolve part of this gap with the proposal of risk reduction versus investment decision framework. Here, a case study of maintenance of existing natural infrastructure is tested against intensified hurricane-driven flood conditions through the end of the century. The results of the study and the value of the framework enable stakeholders to address forecast uncertainty, and make well-timed investment decisions that allow for adaptability, as climate changes. The intent of this research is to create a replicable methodology that, at the census-tract level, determines if the impact of natural infrastructure is a worthwhile investment for any coastal community that is subject to recurrent or extreme-event drive flooding.

Background and Case Study

Through intensified weather events or sea-level rise, climate change impacts the Department of Defense (DoD), which possesses a number of coastal installations, operationally and functionally (GAO, 2019). In an effort to address these concerns, a plan was published in September 2021 recapturing U.S. efforts over the last decade, with renewed focus (DOD, Office of the Undersecretary of Defense (Acquisition and Sustainment), 2021). A companion piece published in November describes five major lines of effort (LOE). This study is aligned with LOE Number 3, protection of military installations via resilient built and natural infrastructure, which highlights the need for community and defense collaboration (Office of the Deputy Assistant Secretary of Defense for Environment and Energy Resilience, 2021). Florida ranks in the top five states for military spending, and is also home to six of the ten most climate-vulnerable military installations (GAO, 2019).

Tyndall Air Force Base was selected as a case study due to the availability of data and recent exposure to weather damage, and candidacy for alternative solutions. The justification for resilient infrastructure can be made based on the catastrophic hurricane season in 2018, when Hurricane Michael devastated Tyndall Air Force base. The only Category 5 storm to hit the Florida panhandle resulted in damages over $25 Billion across the region, destroying valuable power sources, homes, and left a wake of destruction heretofore unseen by the region (Rodysill et al, 2020). Between wind fields and surge-driven flooding, the base sustained $5 billion in damage that will require a decade-long reconstruction effort. In addition to storm surge, recurrent flooding and rising sea levels threaten mission security as weather events intensify. Although the base has now experienced a catastrophic storm event, and forecasts show intensified future storms for the region, reconstruction efforts are ongoing and thus should be focused on adaptations that lower the probability of future damages.

The location of the installation provides natural resources that can be encouraged to deliver supplementary defense in the face of rising construction costs and forecast uncertainty. Barrier islands, located south of the installation and across the surrounding area, minimize coastal flooding naturally. Notably, these structures are sensitive to changing climates, and respond in one of three ways: migration towards land, complete disintegration, or drowning in place (Moore, et al, 2010). As sea level rises, even without exacerbated wave conditions created by hurricanes, barrier islands are lost and no longer provide wave attenuation. If maintained, these structures could provide additional protection against intensified conditions, and have a lower up-front implementation cost than other traditional solutions, like stormwater sewer capacity expansion or elevation of existing facilities. However, an in-depth study of efficacy has not been conducted for smaller communities with respect to future intensified predictions. This research is intended to evaluate the efficacy of barrier island maintenance against a do nothing alternative in an effort to protect the base against intensified storm surge events.

Problem Statement

Future climate conditions will drive intensified extreme event flooding and stress coastal infrastructure. Coastal communities and DoD installations alike are at risk of increased damages, and must adapt to dynamic weather events. Current protective techniques tend to be reactive and bypass unconventional, proactive and approaches with option value. Traditional engineered solutions are effective, but cost prohibitive, disruptive, and time intensive. Natural infrastructure is low cost and noninvasive, yet lacks modeling and analysis required to trigger implementation practices.

This thesis models the damage posed by intensified hurricane events over the remainder of the 21st century, and proposes natural solutions to bolster protections traditionally offered by barrier islands versus a do nothing alternative. This approach holds to the potential to be a cost-saving alternative to total reconstruction of stormwater infrastructure and raised building foundations, but that aspect is not studied within this research. Additionally, barrier island maintenance can reduce recurrent flood vulnerability, and provide tangential environmental and recreational benefits. This study uses Federal Emergency Management Agency (FEMA) Hazus flood modeling software to forecast future probabilistic storm surge based on sea-level rise, tide conditions, and intensified wind fields, and produce flood vulnerability maps for pre- and post-adaptation states.

Research Objectives

This thesis is focused on development of a framework to evaluate the performance of barrier islands as a protective infrastructure asset to reduce future extreme event-driven flooding from intensified climate conditions. To accomplish this, research has addressed the following:

1. Do barrier islands reduce built infrastructure damage tied to hurricane-drive storm surge?
2. Does barrier island maintenance offer a cost-effective alternative?
3. Is there an appropriate mechanism in place for coastal installations to pursue solutions of this type in a fiscally-constrained environment?

Scope and Approach

To accomplish stated research objectives, this thesis follows a traditional format in which Chapter 2 discusses relevant literature associated with traditional, natural, and soft infrastructure solutions, intensified climate conditions, and DoD investment pathways related to construction techniques. Chapter 3 details thesis data and methodology and Chapter 4 covers results and creates an opportunity portfolio that allows stakeholders and decision makers to balance risk, benefit, and uncertainty with respect to adaptation implementation through the end of the century.

II. Literature Review

Chapter Overview

The purpose of this chapter is to summarize the relevant research and previous work associated with extreme-event intensification, current U.S. and Air Force policy, and adaptation opportunities not otherwise explored in the introduction. These topics are combined with the case study data and results in Chapters 3 and 4 to articulate the conclusions of this thesis discussed in Chapter 5.

Extreme Event Intensification

Hurricanes cause the most death and destruction of all recorded weather events in U.S. History. The 2017 Hurricane season produced the highest costs to date: $306.2 billion dollars of damage across 16 named storms. Extreme weather events are growing in number and intensity. From 2018 to 2020, there were 50 weather and climate related disasters with losses exceeding $1 billion, and extreme event strength and frequency are predicted to increase through the end of the century (NOAA Office for Coastal Management, 2022)

Hurricanes are becoming more destructive with added climate change triggers, such as rainfall production, rising global temperature, and most notably, sea-level rise. Heavy rainfall leading to inland flooding accounts for 60% of non-surge related deaths from tropical storms (National Weather Service, 2022). Hurricanes and Tropical Cyclones in the Atlantic basin are stalling more frequently, leading to slow-moving storms that produce higher levels of rainfall that existing stormwater infrastructure is unable to manage, leading to unprecedented flood damages (Hall, 2019). Greenhouse gases are widely responsible for heightened temperature around the globe, and the ocean has absorbed 90% of excess heat. Warmer water leads to higher wind speeds, and probability of storms reaching named storm status increases each decade (Kossin, 2014, IPCC Working Group II, 2018). Global sea level hit a new record high in 2020 and the rate accelerates every year, which impacts what is often the most destructive aspect of a hurricane: the resultant storm surge (Lindsey, 2020; NOAA, 2022). Heavy rainfall and tidal conditions, increasing temperature, and rising sea levels are considered in the following study as intensification factors. These factors, coupled with a range of threat profiles and time horizons, form the basis for Chapter 3 of this thesis. Three of the most damaging storms from the 2020 season experience rapid intensification prior to landfall. Hurricane Michael, the most damaging storm ever to hit the Florida panhandle, also experience rapid intensification. The additional threat of rapid intensification creates an added challenge for coastal communities and DoD officials alike, as dynamic storm intensities and trajectories can be crucial during response efforts.

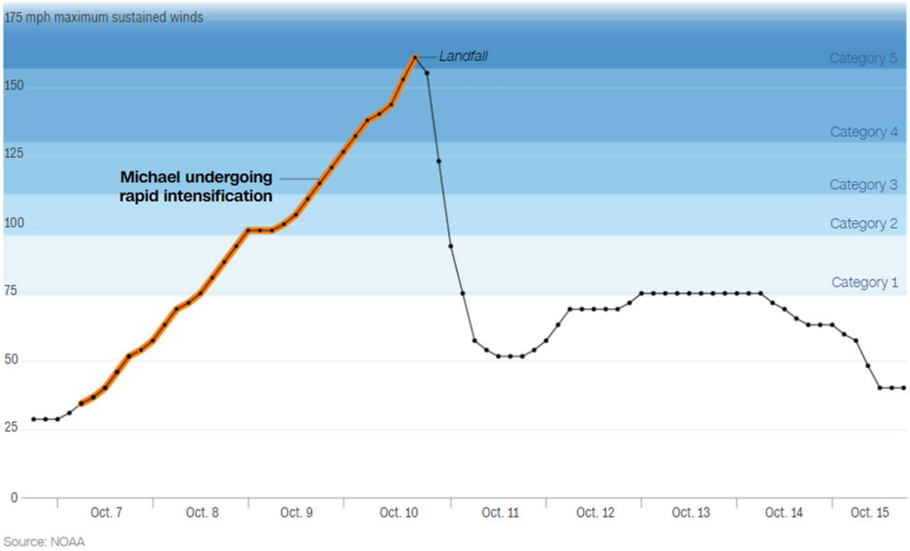


Figure 1. Hurricane Michael Intensification Timeline. Rapid intensification refers to how quickly wind speeds increase during extreme events. Hurricane Michael's intensification timeline was anomalous in many aspects, but particularly with respect to intensification and wind speed (Figure: NOAA, Seinkbeil, et al 2020).

Current U.S. and Air Force Investment Policy

Federal interest in coastal protection via natural infrastructure was catalyzed by Superstorm Sandy in 2012, resulting in a push towards resilient infrastructure solutions as part of the Disaster Relief Appropriations act in 2013. The Obama Administration published a Climate Action Plan soliciting sustainable and innovative solutions that considered investment into natural infrastructure (Executive Office of the President, 2013). Most recently, the Biden administration published Executive Order (EO) 14057, Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability which states that "through a coordinated whole-of-government approach, the Federal Government shall use its scale and procurement power to achieve climate resilient infrastructure and operations” among many other initiatives. Many administrations over the last decade have attempted to bolster resilience and natural solutions to climate change through investment in coastal restoration efforts such as The Disaster Recovery Reform Act of 2018, which provides a singular potential source of funding for climate resilience projects through Presidential appropriation of grants (FEMA, 2021). This funding source is one of few that encourage implementation of pre-disaster hazard mitigation projects rather than reactive investments. As of 2019, the Government Accountability Office identified alternative options for funding through collaboration with states, local authorities, and private partners, bolstered by federal incentives and policy-based adaptations. However, the federal government does not have a strategic approach to guide investment, leading to funding and execution pathways that are ill-defined and undeveloped (GAO, 2019).

The United States Air Force, like other branches, must allocate funding across people, equipment, and infrastructure. Although at face value budgets appear large, the infrastructure portfolio is expansive and aging rapidly and funding must be spread to slow failure conditions. On an annual basis, each base compiles a comprehensive list of asset conditions, value, an importance to mission continuation; this information in filed into an asset management plan that then informs an integrated priority list of infrastructure in need of repair or construction to ensure mission success. Preventative efforts, like coastal restoration, will typically score poorly against degraded assets that currently contribute to the mission. Notable exceptions to this policy are the Oyster

Restoration at MacDill Air Force Base and the four pilot projects currently underway at Tyndall Air Force Base to restore barrier islands, repair damaged wetlands, and trap sediment (Kirkpatrick, 2004, Tyndall Program Management Office, 2021). These opportunities are funded through the Department of Defense's Readiness Environmental Integration Program, intended to assist military installations in funding innovative projects. However, these opportunities are joint-efforts with contributing partners and require collaboration and provided capital for award (Warns, 2021). Opportunities of this type are the start of an important paradigm shift from reactive investment to proactive defense against climate change, and require more research and proven efficacy to trigger implementation.

Adaptation Opportunity

Coastal management offers two opportunities most frequently: traditional constructed infrastructure and soft, policy adaptation to offset damages wrought by extreme storm events. Built infrastructure such as seawalls, breakwaters, levees, and culverts, has dominated protection opportunity due to the expertise and experience with this approach, with significant weaknesses. These include a lack of adaptability, short lifespan, aggravation of adjacent coastlines, and negative impact on local ecosystems (Spalding et al., 2014; Gittman et al, 2016, Hauser et al, 2015).

Risk reduction efforts in the form of policy adaptation typically recommend modification of structures or retreat, which are both met with economic opposition.

Coastal counties account for less than 10% of U.S. total land mass excluding Alaska, yet contribute of 46% of U.S. Gross Domestic Product (NOAA, 2019). Additionally, soft adaptations are difficult to enforce and even more challenging to adopt in communities where revenue is primarily dependent on property taxes associated with coastal sightlines and laws and constituents limit revenue generation elsewhere (Shit et al, 2018).

Natural infrastructure alternatives have been found to benefit coastal communities in several studies, while also providing risk reduction in the form of wave attenuation and surge reduction (Ferrario et al., 2014, Spalding et al., 2014, Sutton-Grier et al, 2015). Co-benefits to the community include fishery habitat creation, carbon storage, and recreational uses. Furthermore, natural alternatives have the potential to self-recover after an extreme event and are on average less expensive to implement than traditional options (Gittman et al, 2015). This option has little cost-to-benefit research documented at a local scale and lacks a defined mechanism for implementation. Additionally, protection provided by natural adaptations is variable in nature and dependent on geography and storm type; thus, additional research is necessary (Sutton-Grier et al, 2015).

Extreme Event Modeling

Although prevalent in nearly every locale, extreme event modeling is challenging for risk and emergency management due to a lack of widely available tools, guidance, time and financing to undertake rigorous risk assessment (Natsev and Todorov, 2012). Frequency of occurrence for extreme events has escalated in the last decade, and existing literature cites forecasts historic data from National Weather Service, Weather Research and Forecasting, and National Oceanic and Atmospheric Administration to predict the damages associated with future event probability (Busal et al, 2020). Though other products exist, like Hazus-MH, developed by FEMA, has proven to be a popular tool in the United States due to nationally applicable standardized data, comprehensive database of predefined structures, and open-source software (Scawthorn et al. 2006a ,Gutenson et al, 2015, Ghimire and Sharma, 2021). For the purposes of this study, Hazus was selected for use because it incorporates flood depth grids, and the result of interest was surge flood depth. Additionally, Hazus reports damage at the census tract level, which is effective for the case study selected as Tyndall Air Force Base is contained within its own census block.

Summary and Way Forward

Though the aforementioned studies have provided significant contribution to natural infrastructure alternatives and implementation recommendations for flooding, there is a lack of research with respect to adaptation performance against extreme events and their predicted intensification through the end of the century. Chapters 3 and 4 are intended to narrow the gap in available research on performance of alternatives against extreme events and provide a replicable framework for coastal communities to assess loss avoidance opportunities, risk intensification, and funding pathways.

III. Chapter 3

Data

A recent assessment of modeled hurricane risk to coastal Florida indicated that extreme storms are characterized by intensified factors of wind speed, sea level rise, and mean sea level (Baldwin et al, 2021). In light of extreme-event projections, performance of barrier islands has not been modeled to determine efficacy as a protective solution against storm surge. To build an evaluation framework for barrier island performance against future events, four inputs were required: a storm profile, threat scenario, time horizon, and intensification factors. Using the Federal Emergency Management Agency's (FEMA) Hazus, a storm modeling software designed to analyze simulated events down to the census tract level, these inputs were combined to create a loss avoidance estimate with respect to maintenance of existing barrier islands.

The storm profile selected for evaluation was Hurricane Michael, provided through the National Oceanic and Atmospheric Association (NOAA) Hurricane Center. The data included temporal latitudinal and longitudinal coordinates of the historic hurricane in accordance with respective wind speed and radius. Additional description of variables is included in the Methods section. The data used is available in Table 1.

HAZUS TABLE FORMAT						
Latitude (decimal degrees)	Longitude (decimal degrees)	Time (hrs)	RMW (miles)	MWS (mph)	Pressure (mbar)	Inland
26.6	-86.5	0	15	127	953	x
27.1	-86.5	3	15	130	947	x
27.7	-86.6	6	15	138	945	x
28.3	-86.5	9	15	139	943	x
28.6	-86.4	10	15	140	937	x
28.8	-86.3	11	15	142	937	x
29.0	-86.3	12	15	144	933	x
29.1	-86.2	13	15	145	933	x
29.3	-86.1	14	15	146	931	x
29.4	-86.0	15	15	148	928	x
29.5	-85.9	15.5	15	150	923	x
29.6	-85.8	16	15	150	923	x
29.9	-85.7	17	15	150	919	x
30.0	-85.5	17.5	15	160	919	✓
30.2	-85.4	18	15	155	920	✓
30.4	-85.3	19	15	150	922	✓
30.6	-85.2	20	15	140	927	✓
30.9	-85.1	21	15	125	932	✓
31.1	-84.9	22	15	115	940	✓
31.1	-84.9	23	15	100	950	✓
31.5	-84.5	24	15	92	955	✓

Table 1. Raw Storm Data: Hurricane Michael

To further evaluate the outputs from Hazus, a topographic digital elevation model (DEM) from the United State Geological Survey (USGS) for the census tract was incorporated into the program to assess flooding and coastal surge risk to the installation. This is a required input for the program to illustrate surge extent based on mean sea level and the elevation of the impacted area. Additionally, median sea level and high tide conditions for the Panama City Beach region were procured from NOAA, to inform the sea level conditions at which the design storm was run, thus creating a more accurate worst-case scenario.

The threat profiles and time horizons selected for evaluation are aligned with the Department of Defense Sea Level Rise (DRSL) database, which are affiliated with politically determined climate tipping points and average design life of constructed measures (Lenton, 2011, Hall et al, 2016). The DRSL database has forecasted sea level conditions for installations at 2035, 2065, and 2100, selected for various climate tipping points and design life of built infrastructure. These planning horizons, which are considered based on a 2016 study that considered non-probabilistic but plausible future conditions to enable risk-based decisions on best available science. However, the study places the onus on the user to consider a range of possibilities to assess risk and response options past the 20-year recommendations, and asserts that an ongoing assessment of conditions should occur for the most appropriate rate of sea level rise (Hall, et al, 2016). Site-specific projections for Tyndall Air Force Base can be viewed in Table 2.

Table 2. DRSL Site-Specific Sea-Level Rise projections for Tyndall AFB through 2100

Global Scenario	Site Specific Projections (ft)		
	2035	2065	2100
Lowest	0.3	0.3	0.4
Low	0.3	0.7	1.3
Medium	0.7	1.3	3
High	0.7	2	4.9
Highest	1	2.9	6.9

Table 2. DRSL Site Specific Projections: Tyndall AFB

Due to uncertainty in forecast conditions as discussed in the introduction, the Coastal Assessment Regional Scenario Working Group (CARSWG) developed five threat scenarios based in NOAA data and emissions based Representative Concentration Pathways (RCP), and three were selected for consideration in this study: Lowest, Medium, and Highest.

Using the intensification factors outlined in previous research, multipliers fit to exponential trends outlined in previous literature were applied to historical hurricane data to determine the storm impact in each threat and time horizon (Baldwin et al, 2021). Intensification factors are numerical factors multiplied by wind field speeds, sea level rise, high tide conditions, and mean sea level. These inputs, coupled with the data described above, provide the baseline for a risk framework specific to Tyndall Air Force Base that can be replicated for coastal communities across the nation.

Finally, to determine the impact of the barrier islands, spatial data of the census tract area and surrounding marine environment was provided by ArcMap functions within Hazus for evaluation of the existing infrastructure against sea level rise. This data is open-source and available through FEMA. The spatial results allow for a basic economic evaluation at a cubic yard level via cost estimates from the United Sates Army Corps of Engineers (USACE) data from Jacksonville, Florida. (USACE Data Center, 2018).

Methods

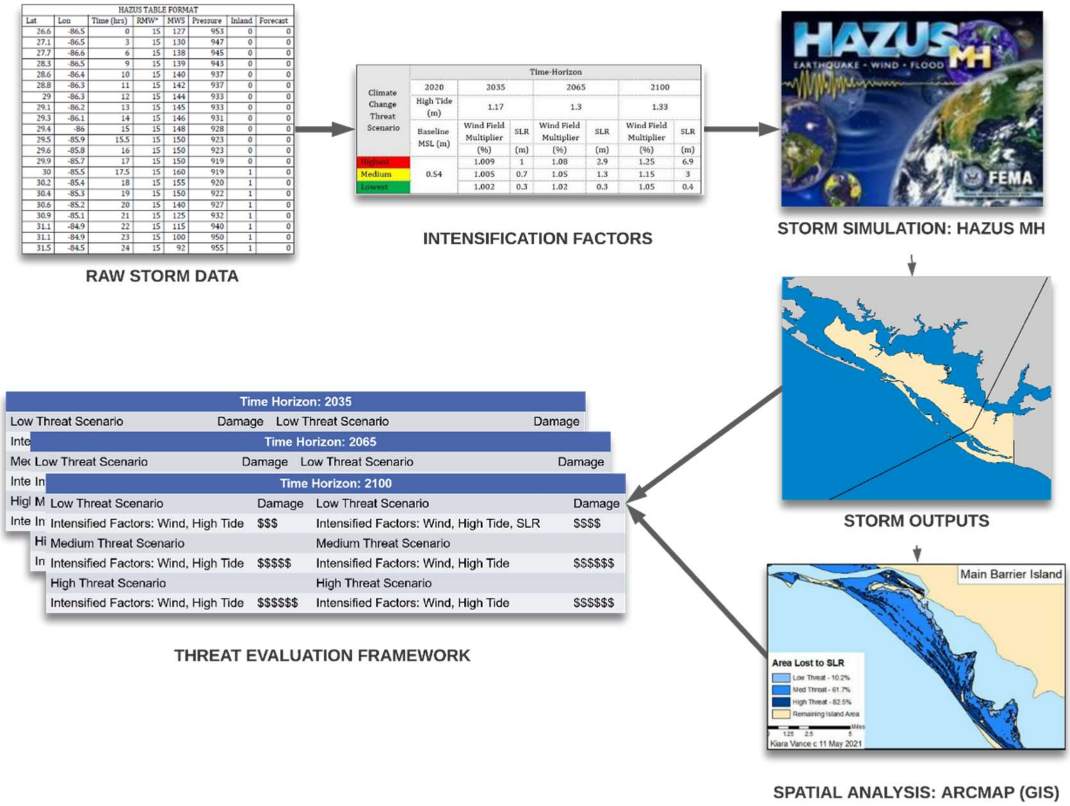
In any evaluation of infrastructure investment, there is the option to do nothing and maintain the status quo. To address the stated research objectives, three areas of focus were established: dynamics, economics, and policy, with respect to if barrier islands are effective in the face of extreme event intensification, cost of barrier island maintenance versus damage avoidance, and the current status of nature-based adaptations in political recommendation.

Notionally, there are three alternatives for comparison: do nothing, barrier island maintenance in the guise of natural infrastructure, and traditional infrastructure investment. Traditional infrastructure construction, such as stormwater sewer capacity upgrades or hardened seawalls, are always available for selection but require a larger up-front cost that may not provide option value to the community. There is additional risk associated with constructed alternatives, in that increased stormwater capacity systems do not prevent base inundation; their purpose is floodwater removal at a faster rate. Thus, mission stoppage will still occur and will persist for a longer time period. However, it should be noted that only nature-based adaptations versus do nothing alternatives were considered in this research, and expense and efficacy of traditional solutions must still be evaluated along with economic trade-offs for a complete evaluation of alternatives.

While natural alternatives typically boast a lower implementation cost, there must still be a balance between their projected value and avoided losses. To determine the value of barrier island maintenance versus the do-nothing alternative, a time and risk scenario portfolio was developed to offer a framework of investment options to coastal communities. Our portfolio shows implementation options from approximately $900,000 to $600 Million at nine time and threat combinations to decrease associated risk based on the preference of the decision maker.

Dynamic Analysis

To analyze efficacy of barrier islands, the framework evaluates storm damages for nine scenarios across three threat and time horizons using a ‘no action’ alternative for comparison. Each simulation was compared against a predeveloped baseline storm which mirrored aspects of Hurricane Michael. There was a total of 18 intensified design storms developed, for which efficacy of island maintenance was determined using relative damages produced by Hazus. To determine the impact of the existing barrier islands, each scenario was replicated with the added factor of island maintenance in the form of dredging. This allowed a relationship between the islands at their current elevation to be evaluated relative to local sea levels and projected sea levels based on census tract damage estimates. Because these loss estimates are relative to the data available from the census, this study used the ratio of adapted to unadapted damages to create a damage escalation factor, hereafter referred to as DEF. The resultant loss avoidance as determined by the simulation allowed for interpretation of island efficacy in the form relative change rather than precise numbers. The methodology for this is illustrated in Figure 2.



HAZUS TABLE FORMAT

Lat	Lon	Time (hrs)	RMW*	MWS	Pressure	Inland	Forecast
26.6	-86.5	0	15	127	953	0	0
27.1	-86.5	3	15	130	947	0	0
27.7	-86.6	6	15	138	945	0	0
28.3	-86.5	9	15	139	943	0	0
28.6	-86.4	10	15	140	937	0	0
28.8	-86.3	11	15	142	937	0	0
29	-86.3	12	15	144	933	0	0
29.1	-86.2	13	15	145	933	0	0
29.3	-86.1	14	15	146	931	0	0
29.4	-86	15	15	148	928	0	0
29.5	-85.9	15.5	15	150	923	0	0
29.6	-85.8	16	15	150	923	0	0
29.9	-85.7	17	15	150	919	0	0
30	-85.5	17.5	15	160	919	1	0
30.2	-85.4	18	15	155	920	1	0
30.4	-85.3	19	15	150	922	1	0
30.6	-85.2	20	15	140	927	1	0
30.9	-85.1	21	15	125	932	1	0
31.1	-84.9	22	15	115	940	1	0
31.1	-84.9	23	15	100	950	1	0
31.5	-84.5	24	15	92	955	1	0

Climate Change Threat Scenario	Time-Horizon						
	2020	2035		2065		2100	
	High Tide (m)	1.17		1.3		1.33	
	Baseline MSL (m)	Wind Field Multiplier (%)	SLR (m)	Wind Field Multiplier (%)	SLR (m)	Wind Field Multiplier (%)	SLR (m)
Highest	0.54	1.009	1	1.08	2.9	1.25	6.9
Medium		1.005	0.7	1.05	1.3	1.15	3
Lowest		1.002	0.3	1.02	0.3	1.05	0.4

Time Horizon: 2100

Low Threat Scenario	Damage	Low Threat Scenario	Damage
Intensified Factors: Wind, High Tide	$$$	Intensified Factors: Wind, High Tide, SLR	$$$$
Medium Threat Scenario		Medium Threat Scenario	
Intensified Factors: Wind, High Tide	$$$$$	Intensified Factors: Wind, High Tide	$$$$$$
High Threat Scenario		High Threat Scenario	
Intensified Factors: Wind, High Tide	$$$$$$	Intensified Factors: Wind, High Tide	$$$$$$

Figure 2. Theoretical Analysis Diagram. A baseline storm, in this case Hurricane Michael, was replicated in a storm simulation. This simulation was then compared against future hurricanes that are multiplied against factors that are intensified based on climate predictions for future years and risk profiles. The outputs from these simulations were then coupled with spatially analyzed area losses relative to the intensified values from existing natural infrastructure to develop a framework of protective worth.

Storm Inputs

FEMA’s Hazus Storm Simulation Software has capability of running both historical and probabilistic storm tracks. The latter allows users to create storms based on user-defined parameters. In order to illustrate the performance of barrier islands against future, intensified storms, raw storm data from Hurricane Michael was provided by NOAA’s Hurricane Center. The required data included latitudinal and longitudinal coordinates, wind speeds, radius to maximum wind speeds, and whether the storm was inland or at sea at a given time. Latitudinal and longitudinal coordinates are based on the storm track selected. In this case, exact coordinates were predetermined by the National Hurricane Center as the baseline storm was historic rather than probabilistic. Wind speeds influence the model in that the higher the wind speed, the additional force behind storm surge calculations within Hazus. Wind speeds determine category severity for named storms, and this research was focused on a worst-case scenario. As with the track coordinates, the radius to max wind speeds and inland/at sea determinations were not altered from Hurricane Michael; these impact the amount of and location of affected areas following an extreme event. The final input for Hazus is the mean sea-level. As this variable increased with DRSL projections, resultant surge flood damages also increased. Because Hazus damage estimation software must run wind field damage estimation to produce an estimated surge map, all of the listed variables had to be considered when establishing a projection of Hurricane Michael into 2100.

As threat horizons grew in severity, damage estimates increased, although not in a linear fashion. Across time horizons, 2035 loss estimates were significantly lower than 2065 and 2100 estimates in any scenario, as risk factors that contribute to intensified extreme event flooding like warmer oceans and higher sea levels are still manifesting in today's climate.

Intensification Factors

A previous study determined predictive multipliers for intensification factors based on time and threat horizons as determined by the Department of Defense Regional Sea Level Rise (DRSL) database for nearby Eglin Air Force Base, Florida (Baldwin, 2021). The factors determined to have the highest impact on intensified storms are wind strength, sea level rise, and tidal conditions. To derive the wind strength multiplier, potential ranges for forecasted wind speed were evaluated and fit to an exponential trend line at 5% intervals based on the respective threat scenario (Bhatia et al, 2018, Baldwin et al, 2021). High tide and mean sea level conditions were developed through NOAA's tide prediction calendar and averaged across 12 months for each respective year, 2035, 2065, and 2100. Through combination of the multipliers developed for wind field, DRSL forecast sea levels at the lowest, medium, and highest risk scenarios specific to Tyndall Air Force Base, and high tide conditions from the nearest NOAA station in Panama City, a portfolio of factors was developed from 2020-2100 and multiplied against the baseline storm to create a set of 9 storms, one for each year and threat scenario. Those storms were then replicated with the addition of sea level rise estimates within Hazus to generate a forecast decision framework for risk analysis. Factors can be viewed in Table 3.

Table 3. Scenario Intensification Factors. The factors outlined in this table are collected from previous studies and current projected data from NOAA and the DRSL database for Tyndall Air Force Base. These multipliers are then coupled with historical storm data to produce a range of intensified storms with which evaluation of barrier island efficacy is possible.

<table>
<tr><th rowspan="4">Climate Change Threat Scenario</th><th colspan="7">Time-Horizon</th></tr>
<tr><th>2020</th><th colspan="2">2035</th><th colspan="2">2065</th><th colspan="2">2100</th></tr>
<tr><th>High Tide (ft)</th><td colspan="2">1.17</td><td colspan="2">1.3</td><td colspan="2">1.33</td></tr>
<tr><th>Baseline MSL (ft)</th><th>Wind Field Coefficient</th><th>SLR (ft)</th><th>Wind Field Coefficient</th><th>SLR (ft)</th><th>Wind Field Coefficient</th><th>SLR (ft)</th></tr>
<tr><td>Highest</td><td rowspan="3">0.54</td><td>1.009</td><td>1</td><td>1.08</td><td>2.9</td><td>1.25</td><td>6.9</td></tr>
<tr><td>Medium</td><td>1.005</td><td>0.7</td><td>1.05</td><td>1.3</td><td>1.15</td><td>3</td></tr>
<tr><td>Lowest</td><td>1.002</td><td>0.3</td><td>1.02</td><td>0.3</td><td>1.05</td><td>0.4</td></tr>
</table>

Table 3. Intensification Factors

Storm Simulation

The Hazus simulation methodology provides officials with decision support software for loss estimation with respect to hurricane scenarios. This capability enables users to visualize and communicate consequences of future hurricanes, develop risk reduction strategy, and mitigate storm effects. Hazus software is Geographic Information

System (GIS) based, and utilizes the National Oceanic and Atmospheric Administration's (NOAA) Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model and Simulating Waves Nearshore (SWAN) models for surge analysis (FEMA, 2018; Baldwin et al, 2021).

Storm Outputs

Simulation outputs include surge extent maps, estimated losses, and facility-type specific damages and losses. Due to the nature of force protection and base security, the facility data for Tyndall Air Force Base is not available. Thus, a building-to-building estimate of loss avoidance cannot be calculated for a framework of this magnitude. As a result, comparisons of damage estimates were evaluated to determine loss avoidance between no action and island maintenance alternatives using pre and post adaptation measures, derived by the equation below.

$$DEF_i = \frac{Unadapted\ Damages_i}{Hurricane\ Michael\ Damages} - \frac{Adapted\ Damages_i}{Hurricane\ Michael\ Damages}$$

Equation 1. Damage Escalation Factor Equation

Where the damages associated with adaptation states are produced using Hazus flood estimates relative to historical Hurricane Michael and *i* refers to a specific scenario. For example, the DEF calculation for 2100, High Risk scenario is shown in Equation 2.

$$DEF_{2100,High} = \frac{\$41.5M}{\$2.63M} - \frac{\$7.2M}{\$2.63M} = 13.04$$

Equation 2. Example DEF Calculation

Hurricane Michael's simulated losses were used as a baseline assessment, as it is the worst storm to have hit the panhandle of Florida. Storm intensification creates unavoidable losses when Category 5 hurricanes are considered, but there is opportunity to downgrade estimated damages with intervention.

Spatial Analysis

In order to determine the impact of island loss to sea level rise, and the generalized cost of maintenance, a spatial analysis of the protective infrastructure was assessed. Using ArcMap, the shapefiles associated with sea rise levels indicated by high tide and predicted factors were combined and a spatial analysis was completed to determine the extent of the loss and the area in need of maintenance at a square mile approximation.

Area calculations were derived from the NOAA shapefiles through spatial calculation of elevation difference between existing islands and sea level. Losses indicated by future projections of high tide and sea level rise conditions allowed for calculation of the area in need of maintenance. To derive these areas, attributes were drawn from the metadata associated with the shapefiles. New fields were added to the data frame within ArcMap and maintenance area was calculated from projection coordinates after they were transferred spatially to a polygon representative.

$$Total\ Area\ in\ square\ miles = Area\ (m^2) * 3.86102x10^{-7}(\frac{m^2}{mile^2})$$

Equation 3: Unit Conversion

$$Total\ Remaining\ Area\ = Original\ Polygon\ Area - New\ Polygon\ Area$$

Equation 4: Total Remaining Area Calculation

The area remaining, shown in Table 4, was calculated by removing all area where sea level will have inundated the sediment, thereby eliminating surge flooding protection.

Table 4. Area Lost Values, 2100. These areas reflect the 2100 horizon of threat scenarios. The total area of the barrier islands in front of Tyndall AFB is 7.08 mi^2, and sit lower in elevation than most of the base. However, their presence prevents additional surge from inundating the base, and at a High Threat scenario, nearly 83% of the islands are lost.

Threat Scenario	Area Lost to SLR (sq mi)	Percentage Total Area Lost (%)
Low	0.723	10.2
Medium	4.37	61.7
High	5.84	82.5

Table 4. Area Lost Values, 2100 Scenarios

The volume of barrier islands in need of restoration was determined by multiplying area lost by the height of SLR at each scenario, creating an overestimated approximation of dredged material required to sustain the barrier islands. The protective infrastructure assessment is illustrated in Figure 4.

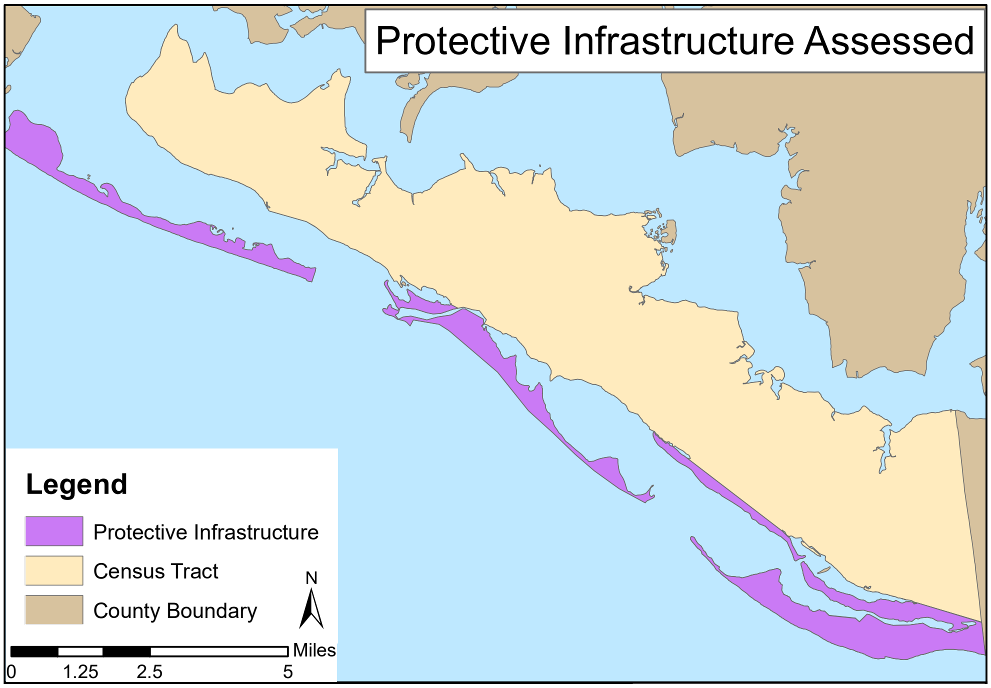


Figure 3. Protective Infrastructure Assessed. The area highlighted in purple indicates barrier island formations that currently exist in St Andrew Bay, south of Tyndall Air Force Base.

Economic Assessment

An abbreviated economic analysis was performed to evaluate the efficacy in investment of strategic sediment placement for existing island maintenance, and an estimate for future investment was created using the United States Army Corps of Engineers (USACE) dredging estimates of $14.86 per cubic yard for Jacksonville, Florida, as it is the closest regional office to Tyndall Air Force Base (USACE Data

Center, 2018). This estimate, multiplied by the area losses to sea level rise associated with the range of forecasted possibilities, generates a decision framework for leaders to execute short-term, nature management loss prevention adaptations. For the purposes of this study, dredging is defined as the removal of sediments and placement thereof to maintain the deposit location where it currently exists. Dredging estimates were used over pure material costs due to inclusion of transportation, engineering and design by cubic yard, in addition to material restriction considerations, as Florida is one of five states that regulate source material for dredging projects on beaches (NOAA, 2000). This tradeoff analysis generalized and highly dependent on volumetric approximation, which is overestimated due to available data and breadth of study. Further economic evaluation in future studies could consider continuity of maintenance or time-step based strategies, alternative stabilization measures and techniques, and increased construction costs. The economic conclusions presented in this research are dependent on the loss estimation, which is relative to damage escalation and not exact.

IV. Chapter 4

Results

Damage estimates increase with threat intensity linearly for low and medium risk scenarios, and exponentially for high-risk scenarios as seen in Figure 5.

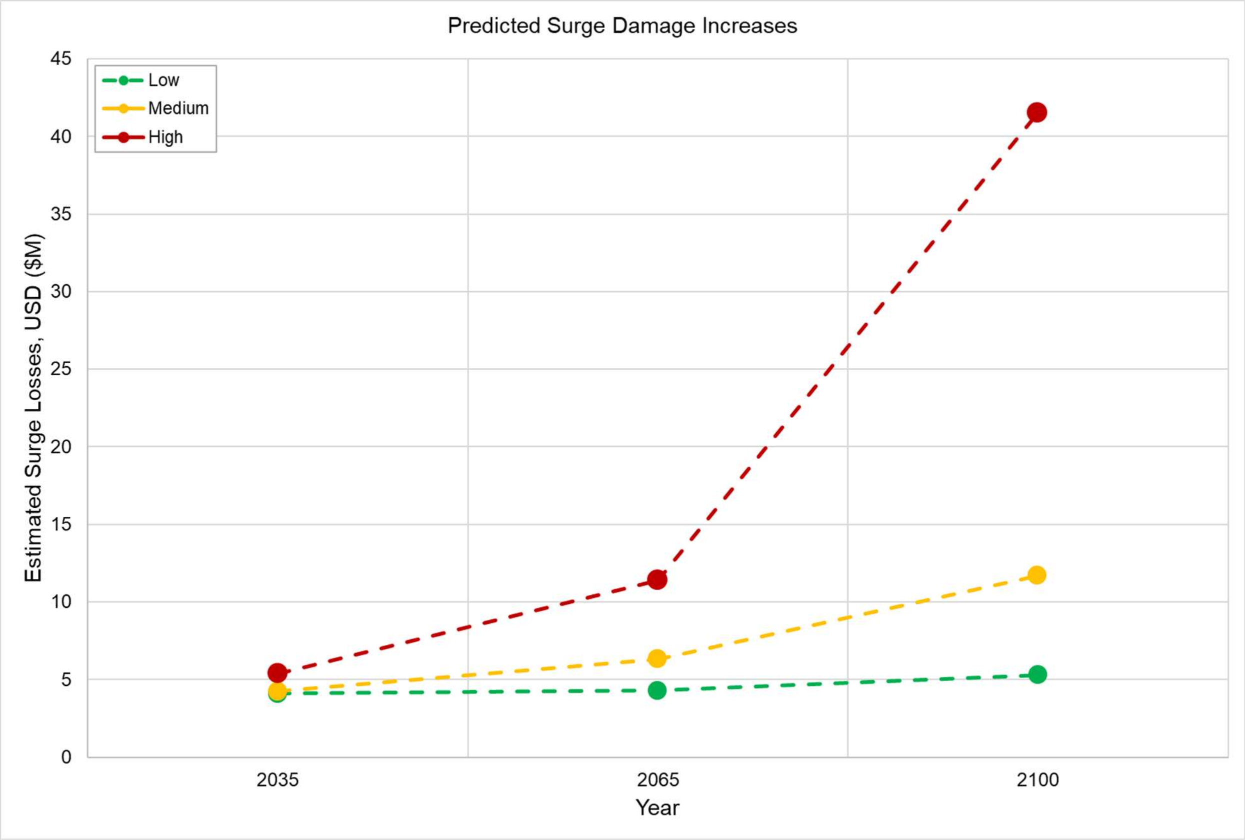


Figure 4. Predicted Surge Damage Increase. The estimated damages from surge flooding without barrier island maintenance increase linearly and exponentially depending on the threat scenario. Cost estimates must be considered conservatively as true facility impact is not available through analyses of this type; these estimates reflect census-tract level data without military facilities included.

Each intensified storm scenario culminates in additional surge flooding damage; however, barrier island preservation reduces potential loss in every time step and threat scenario. At shorter and less intensified scenarios, the value of island preservation is marginal at 6%, i.e., it does not provide a meaningful reduction in losses when compared to the do nothing alternative. However, for long-term and higher risk scenarios, loss avoidance is much greater with maintenance than without. Furthermore, barrier island preservation costs outlined in this framework are overestimated due to the of calculation basis of a rectangular volume rather than a nonstandard volume, which is what would be necessary for true island preservation, as illustrated in Figure 5.

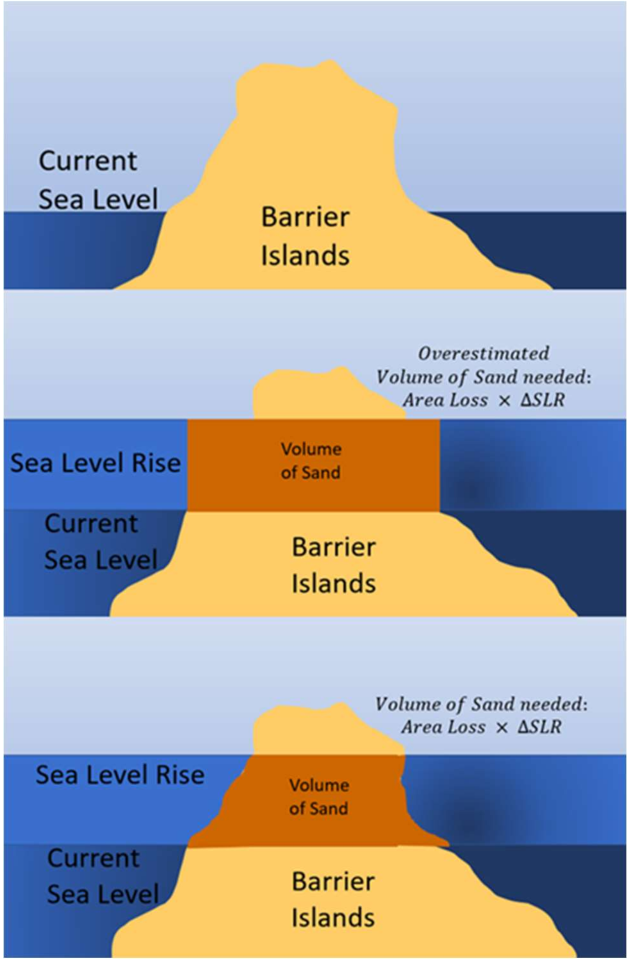


Figure 5. Volume Overestimation Illustration. Available dredged sand cost estimates are in cubic yards from USACE, and this research took a basic estimation approach to determine how much material would be necessary to buffer island losses with increased sea level conditions. However, due to the nature of island variability with tidal conditions, storm seasons, and sand trapping efforts, this estimate is overestimated. Figure 5a is an illustration of current barrier islands, where 5b illustrates the overestimated volume calculation. 5c illustrates a more accurate illustration of volume calculation that should be evaluated in future studies.

Across 18 storms, flood damage increases follow exponential trend lines for each threat horizon. At higher wind speeds, damage estimates from wind max out from available data values, and surge losses continue to rise. The main difference between storms at higher threat levels at the end of the century was primarily determined by surge extent and wave height, as Hazus flood estimations are most sensitive to mean sea level when computing damages. Additionally, there is a maximum wind speed allowable in Hazus simulations, and intensified hurricanes like those simulated in this research reach maximum speeds by the end of the century. As storms continue to intensify and barrier islands are lost to sea level rise, surge wave height and progression onto shore rises exponentially, further highlighting the need for protective solutions.   Area loss values can be seen in Figure 6 for High-Risk, 2100 scenarios, and it is clear that without intervention, median sea level will overwhelm the islands that currently provide protection to the installation by the end of the century.

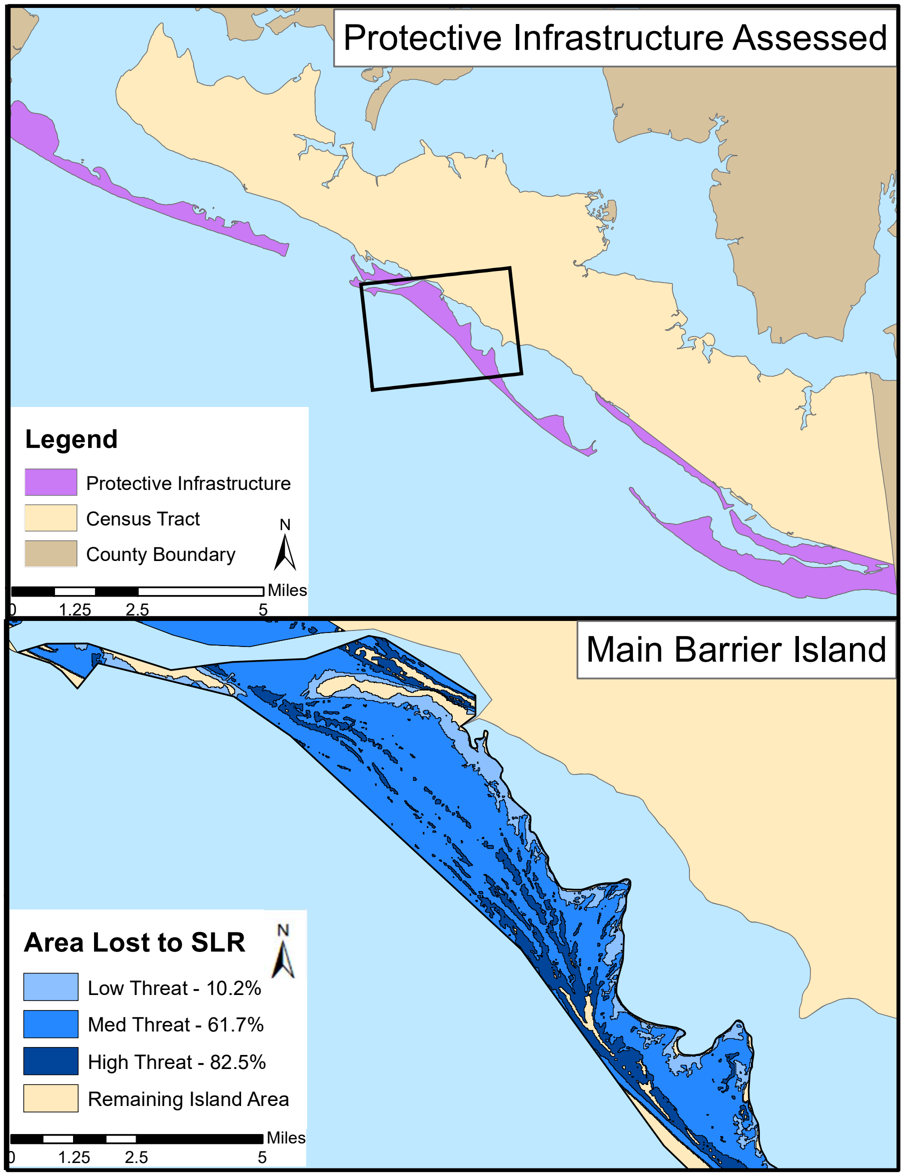


Figure 6. Area Losses for High Risk, 2100 Scenarios. Figure 6a is the surrounding area of assess protective infrastructure, where 6b. shows a magnified illustration of the spatial analysis of area loss with respect to sea level rise scenarios at 2100. Investment costs and loss avoided values derived from this study can be seen in Table 5.

Table 5. Investment vs DEF. Table 5 illustrates the results from this assessment from all 9 time and threat horizons and their decrease in damage from the do-nothing alternative. Although investments range from under $1 million to well over $ 600 million, it is important to note that each time step shows a decrease in possible damages.

Area Lost (sq mi)	Scenario	SLR (ft)	Investment	Damage Escalation Factor
2035				
0.20	Low	0.3	$897,592	0.06
0.72	Medium	0.7	$7,765,318	0.23
0.72	High	1	$11,093,311	0.49
2065				
0.20	Low	0.3	$897,592	0.41
0.72	Medium	1.3	$14,421,304	0.54
1.99	High	2.9	$88,547,023	2.28
2100				
0.72	Low	0.4	$4,437,324	0.53
4.37	Medium	4	$ 268,203,424	1.72
5.84	High	6.9	$ 618,279,473	13.04

Table 5. Investment vs DEF

To better visualize the values in Table 5, damage escalation increase is reflected in Fig. 7. As worst-case events intensify, increased loss is unavoidable as illustrated by the gray bars; losses against storms of heightened magnitude should be expected. However, with use of adaptation, damages can be deescalated. The degree to which losses are avoided is equivalent to the excess loss produced by unadapted scenarios, reflected in red.

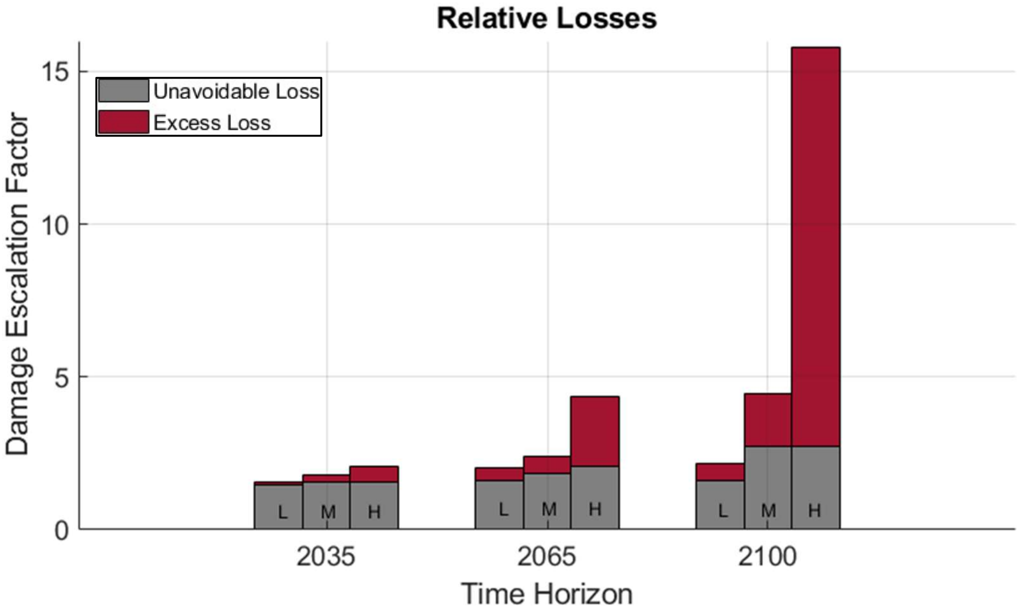


Figure 7. Relative Losses. In Figure 7, damages associated with surge flooding from increased intensity hurricanes are reflected through 2100. Because the selected baseline storm was a Category 5, future storms of this type are projected to be equally devasting, thus incurred damages should be expected no matter the adaptations adopted. However, implementation of natural infrastructure solutions like barrier island maintenance shows a clear decrease in damage escalation between alternatives.

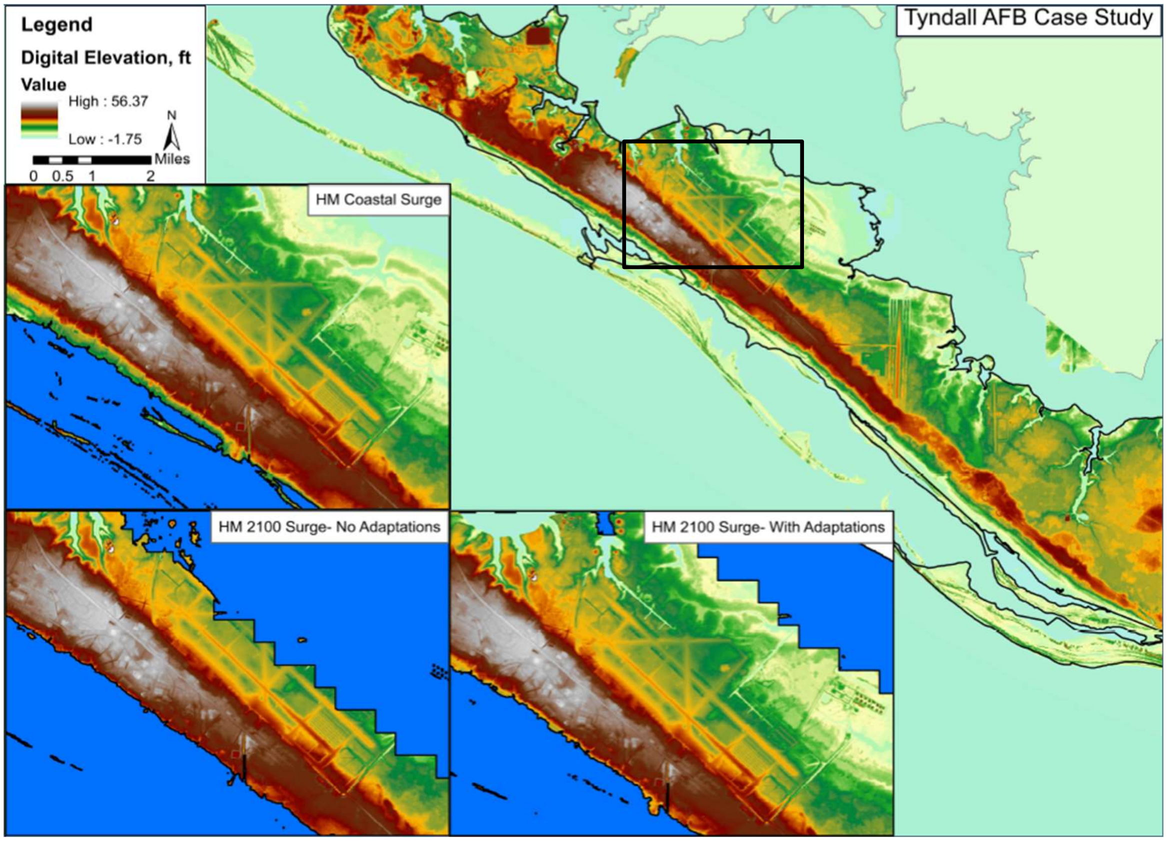


Figure 8. Surge Maps: 8a. Tyndall Air Force Base Census Tract Digital Elevation Map, 8b. Hurricane Michael Baseline Surge Extent, 8c. High Risk, Year 2100 Scenario without Adaptation, 9d. High Risk, Year 2100 Scenario with Adaptation

The final output is a map of the surge wave extent against the elevation map. These shapefiles show the extent to which surge inundates the research area. Figure 9a illustrates the census tract, and 9b shows how far the baseline extent of surge for Hurricane Michael went onshore. 9c and 9d show the reach of surge is clearly limited by use of adaptive solutions. These results, coupled with the loss avoided, is the result of barrier island intervention. Barrier island maintenance, on average, is less costly than recovering installations from flood damage and the secondary and tertiary effects of surge inundation. Mold mitigation efforts alone cost the Air Force hundreds of millions of dollars as a direct result of Hurricane Michael flood damages. Investment into natural infrastructure alternative, and barrier island maintenance in particular, is a clear choice to reduce annualized losses without overinvesting in solutions that may not prove valuable as climate changes.

V. Chapter 5

Discussion on Policy and Community Implications

The Department of Defense has been working to increase resilience of installations for the better part of a decade, by integration of climate information into playbooks and building codes (Department of Defense, 2021). The FY2020 Energy and Water Development appropriation bill included investments required to improve and maintain flood control projects, but was mainly focused on waterways needed for the national supply chain. In 2021, the Biden Administration issued Executive Order (EO) 14008, Tackling the Climate Crisis at Home and Abroad, in an effort to spur the design and implementation of climate policy as it relates to national security. However, current funding avenues impinge on execution of projects with prevention focus due to the requirement that projects focus on mission-dependency and rapidly degrading and aging infrastructure rather than climate resilience. Priority lists, like those used by the Department of the Air Force, are poised to make the most of dwindling budgets but cannot compete with the massive portfolio of infrastructure in need on investment. A behavioral shift is necessary to aid in implementation pathways for projects that are prevention based, like coastal ecology management and strategic sediment placement as evaluated in this research.

Since conception nearly a century ago, beach nourishment and coastal management of natural protective infrastructure has grown steadily with rising sea level and further understanding of negative effects of built marine infrastructure. While beach replenishment goes beyond replacement of lost sediment, this study only considers dredging as a form of coastal nourishment, and additional strategies should be evaluated. Following policy and construction adaptations, over 475 U.S. communities restored beaches and natural sediment collection points with over 1.5 billion cubic yards of sand, and 83% of the total volume of sand placed in these nourishment efforts were placed by six states: California, Florida, New Jersey, North Carolina, New York, and Louisiana. (Elko et al, 2021). Only three of the previous states, California, North Carolina, and Florida, include specific sand requirements in their policy (NOAA, 2000). The United States is also a signatory on The London Convention on the Prevention of Marine Pollution, which stipulates that alternative for marine placement should consider the long-term impacts of the placement activities. Certain states, like California, encourage dredged sediment use as a resource in long term management strategies (EPA, 2017), which should be a strategy that is adopted nationwide. If additional states adopted similar management strategies for sediment placement, maintenance of existing natural infrastructure could be a viable risk reduction asset that is both affordable and practical for coastal communities. It should be noted that the line between hard and natural strategies and soft policy adaptations is not crisp. There is inherent overlap between tangible and soft adaptations, in that if there is a stipulation or requirement published to encourage natural adaptations or protect coastal communities, physical adaptations will accompany a soft policy recommendation.

Efficacy of dredging to support natural sediment placement can be contested based on material quality, as sediments that are relocated can contain pollutants. Open water placement preserves the impact of natural sediment deposition and avoids the majority of negative life-cycle impacts associated with containment islands (Bates et al, 2015). However, strategic sediment placement like what is suggested by this research is being pursued at Tyndall Air Force base as a pilot project with funding from REPI and in accordance with Florida regulation. The *Second Line of Defense Project* through the Tyndall Program Management Office will encourage utilization of innovative methods to build and reinforce enlarged dunes on the south side of the installation by St Andrew Bay, with a final intent to increase dune construction as protective barriers in front of vulnerable areas on the base. This effort is intended to reduce erosion and place native oyster reefs, and restore tidal flats while also creating new barrier islands to increase habitats for threatened and endangered species. Combined with the results of this study, the efforts of the pilot projects could prove to be valuable justification for other coastal communities to implement natural protective infrastructure and thus achieve risk reduction against intensified surge events with option-value.

Extreme surge events impact entire communities and military installations alike. When the surrounding community around a base is affected, there are secondary and tertiary effects that challenge operational ability. Supply chains for materials and equipment, power and communications service, and transportation networks all contribute to operations assurance and are highly impacted by surge events that will accompany intensified hurricanes.

Opportunity Pathways

To determine the appropriate response for decision makers, the next step for this thesis is a Dynamic Adaptive Policy Pathway (DAPP), which is an approach that aims to support the development of an adaptive plan that is able to deal with conditions of deep uncertainty. Future research should evaluate expected cost of doing nothing and traditional alternatives with additional variables. The value we postulate from this research is that natural infrastructure gives decisionmakers the ability to stave off over expenditure and establish an optimal path forward to minimize regret.

Future evaluation of alternatives would deliver a framework that can identify true climate tipping points with cost relative to damages expected, rather than an expected outcome of natural infrastructure implementation versus do nothing alternatives. This research was motivated by a notional pathway for investment opportunity, illustrated in Figure 9, but requires a third dimension, rate of investment, to fully weigh the benefits of engagement. In any future endeavor, there is the option to do nothing and maintain the status quo. Notionally for this study, there are two other alternatives for comparison: barrier island maintenance in the guise of natural infrastructure, and traditional infrastructure investment. Traditional infrastructure construction, such as stormwater sewer capacity upgrades or hardened seawalls, are always available for selection but require a larger up-front cost that may not provide option value to the community. There is additional risk associated with constructed alternatives, in that increased stormwater capacity systems do not prevent base inundation; their purpose is floodwater removal at a faster rate; thus, mission stoppage will still occur and will persist for a longer time period is selected. Natural infrastructure options are often a smaller investment, and allow for future climate predictions to be realized prior to triggering implementation of cost-prohibitive solutions. The subway chart below the notional cost timelines indicates a suggested cost pathway: through selection of natural alternatives at a prescribed year, risk reduction is achieved at a lower construction cost, and selection of this option permits transfer to other alternatives when deemed beneficial.

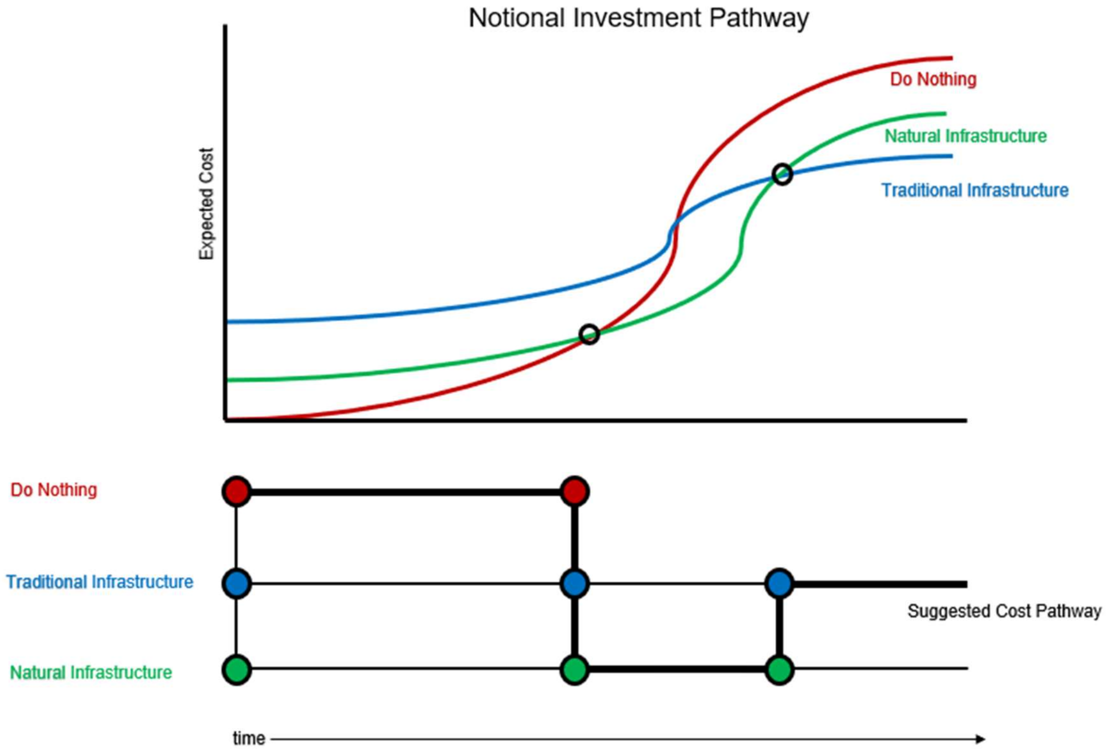


Figure 9a. Notional Investment vs Time and 9b. Investment Pathway. At the lowest cost, there is a do-nothing alternative that quickly becomes the most expensive option in the face of intensified storms. At a slightly higher implementation cost, natural infrastructure staves off increased investment strategies by decreasing damages associated with extreme event flooding. The intersection of these points illustrates where decisions makers have the opportunity to jump off one pathway in favor of another to better serve the interests of the installation. These jumps are shown in a suggested pathway in the subway chart illustrated in 9b.

Research Applications

The results of this study indicate that investment into barrier island maintenance decreases surge extent, thereby creating loss avoidance for necessary networks. Investment with respect to this research is grossly underestimated, and future economic analyses with this study as a baseline could be useful in illustrating return on investment and further advocation efforts for preservation projects of this type. Barrier island maintenance expense is dependent on the rate at which mean sea level rises, which makes a difficult planning horizon when considering protective options into 2100. Small scale efforts over the course of a decade would allow for investment returns in line with intensification factor manifestation without cost prohibitive measures.

Limitations

Areas where this research can be improved include forecasting accuracy of damage predictions, as the current results are a low estimate of the potential damage risk to Tyndall Air Force Base because military facilities are not reflected in their entirety in the program due to security constraint.

Additional limitations to this research include the lack of a facility specific evaluation with respect to storm surge. Due to data restrictions and information available through Hazus, only generalized loss predictions can be evaluated. Hazus utilizes data from the census, which means that only disclosed facilities can be considered. Due to data masking for military facilities, Hazus was used to produce generalized flood damage estimates for consideration in this study. In the case of coastal installations, census tract data is less valuable than building specific damages when advocating for centralized or federal funding. Additional limitations that are associated with the intensification analysis include factor variability within forecast predictions: sea level rise estimates from DRSL are based in bounded probability scenarios developed in 2016. These scenarios may shift with time, and sea level impacts all of the factors that are included in intensification scenarios, like wind speed and rainfall, adding additional changeability that was not considered for this study. Furthermore, for the purposes of this research, only one storm was replicated and intensified within Hazus, and followed the exact same path seen with Hurricane Michael. This creates assumptions within the framework, and alternative storm tracks and intensification scenarios, i.e., slow moving hurricanes and high rainfall hurricanes, should be considered. Further evaluation across different distance intervals would assist in proving the worth of the protective shoreline. The volume of island loss and thus maintenance cost is greatly overestimated, due to volume calculation based on rectangular shapes rather than the exact shape of the island itself. This methodology, however, can be repeated for coastal communities across the United States to determine the investment amount for their naturally occurring infrastructure.

Future coupling of stormwater modelling software with GeoBase GIS and facility data can result in flood vulnerability maps and facility specific impacts that could be developed for pre- and post-adaptation states. Culminations of these studies will result in an investment and policy analysis which could test the feasibility of natural infrastructure implementation as a mechanism to avoid or delay modifications to existing stormwater infrastructure. Future study scenarios could be applied to advise both Department of Defense government entities and coastal communities for future projects aimed to prevent asset loss.

Conclusion

This study resolved, at a census-tract level the opening in framework development through evaluation of existing infrastructure maintenance against intensified conditions through the end of the century. The research outlined in the introduction was accomplished by addressing three primary research objectives:

1. Do barrier islands reduce built infrastructure damage tied to hurricane-driven storm surge?
2. Does barrier island maintenance offer a cost-effective alternative?
3. Is there an appropriate mechanism in place to promote solutions of this type in a fiscally-constrained environment?

The first objective was evaluated through simulation of extreme event flooding across 18 time and threat calibrated scenarios. Compared to traditional solutions, natural adaptations provided flexibility in the face of uncertainty, and multi-realized benefits to not only the installation and local community, but the environment at large. Though the results are dependent on the risk tolerance of decision makers, it is clear that implementation of natural adaptive solutions can offset increased damage probability from intensified storms, and may help avoid more costly hurricane adaptations. Under even the most aggressive scenario, there was a three-fold reduction in damages due to maintenance of barrier islands, and a blended solution of hard and soft adaptations should be pursued for the most impactful solution (Sutton-Grier et al, 2015).

With respect to the second objective, a surface level economic analysis revealed the option value of implementing the portfolio produced in Chapters 3 and 4, but has significant room for enhancement through additional variables and investment assessment. This assessment suggests that there ‘wait-and-see’ time generated by implementing small, low-cost, synthetic natural infrastructure adaptations rather than no-action alternatives. This analysis is relevant given the DoD’s hesitance to make large investments in highly uncertain climate change predictions. Additionally, under less intense projections, barrier island maintenance and other natural infrastructure solutions may provide the risk reduction needed without investment into hard, expensive adaptations for an event that never occurs. Under the high-threat scenario at 2100, the reduction in surge driven damage provided by barrier islands could be enough to lower investment into costlier solutions and provide time for decision makers to limit uncertainty. The impact of natural infrastructure is resoundingly positive and should be afforded consideration alongside traditional adaptations.

Future planning for projects of this nature allows leaders for both bases and their respective coastal communities to bide time while evaluating climate changes over the next century, the impact on extreme weather, and technological advances. Climate change adaptations for coastal communities require iterative research due to the fluidity of factors involved and the dynamic of forecast predications (Wagner et al, 2014). This study contributes to scholarly defense of natural innovation opportunities and provides a new scope that justifies the support of natural infrastructure alternative use rather than no action as climate factors intensify. This study also suggests use of alternative, rather than traditional techniques to prevent widespread damages due to flood events. The supplementary value of this research is that it can inform a "step-off" point where leaders can choose to invest alternatively when forecasted predictions become more certain, without over-investing in solutions that may be overly prescriptive; these adaptations can also have secondary returns on investment in the form of resiliency, community engagement, and bolstered ecosystems.

Extreme events range in damage type and intensity; i.e., Hurricane Michael had a record-breaking intensification timeline and wind speeds, and Hurricane Harvey resulted in historic flooding for a tropical storm (Emmanuel, 2017; Senkbeil et al, 2020). Storms of this magnitude result in damage with impacts that may be impossible to predict; thus, adaptation strategies must be variable and have the capability to be combined with other solutions to create an umbrella for protection. There is no one standard that can account for all climate change related damages, and the strategy outlined in this research can be coupled with other solutions to provide loss avoidance, and encourage preventative construction rather than reactive implementation of traditional strategies after extreme events occur (Baldwin, 2021). Though this research is aimed towards Department of Defense installations, is replicable for coastal communities across the U.S at the census tract level, and provides options for loss avoidance at different investment and threat scenarios pending fund availability and community support.

The third objective was explored via thorough review of existing studies, federal mandates, and U.S. Air Force policy in Chapter 2. Current literature suggests that prevention focused construction is motivated after extensive destruction occurs, and typically only to return to pre-disaster state (Wagner et al, 2014; Senkbeil, et al 2020). Through use of the outlined methodology and framework, advocation for alternative natural adaptations and barrier island maintenance can be achieved at the base level or equivalent project execution element for communities and planners and allows for collaborative work funded via REPI and presidential grant, generating opportunities for the DoD to pursue cost sharing with other government organizations as a way to further reduce direct costs, and increase benefits at the regional-scale. Ultimately, natural infrastructure minimized coastal and surge flooding with respect to intensified hurricanes, and policy recommendations will need to accompany advocation for adaptations of this type. These opportunities are highly cost effective and adaptable, especially when coupled with policy efforts like no-wake zones, and other preservation focused, intangible efforts.

The framework developed in this thesis is intended to enable engineers, ecologists, and community planners to investigate the tradeoffs between infrastructure alternatives. The results of the study and the value of the framework is through enabling stakeholders to address forecast uncertainty, and make well-timed investments that allow for adaptability as climate changes.

Bibliography

Alvich, Jason. "The Poleward Migration of the Location of Tropical Cyclone Maximum Intensity." Text. World. Accessed January 7, 2022. https://www.gfdl.noaa.gov/research_highlight/the-poleward-migration-of-the-location-of-tropical-cyclone-maximum-intensity/.

American Society of Civil Engineers. "ASCE's 2021 American Infrastructure Report Card | GPA: C-." *ASCE's 2021 Infrastructure Report Card* | (blog), January 11, 2017. https://infrastructurereportcard.org/.

Balasubramanian, Muniyandi. "Climate Change, Famine, and Low-Income Communities Challenge Sustainable Development Goals." *The Lancet Planetary Health* 2, no. 10 (October 1, 2018): e421–22. https://doi.org/10.1016/S2542-5196(18)30212-2.

Baldwin, Alexander. "Developing Infrastructure Adaptation Pathways to Combat Hurricane Intensification: A Coupled Storm Simulation and Economic Modeling Framework for Coastal Installations." *Theses and Dissertations*, March 1, 2021. https://scholar.afit.edu/etd/5029.

Bates, Matthew E., Cate Fox-Lent, Linda Seymour, Ben A. Wender, and Igor Linkov. "Life Cycle Assessment for Dredged Sediment Placement Strategies." *Science of The Total Environment* 511 (April 1, 2015): 309–18. https://doi.org/10.1016/j.scitotenv.2014.11.003.

Bevacqua et al., E. "Higher Probability of Compound Flooding from Precipitation and Storm Surge in Europe under Anthropogenic Climate Change." Accessed November 4, 2021. https://www.science.org/doi/10.1126/sciadv.aaw5531.

Bhatia, Kieran, Gabriel Vecchi, Hiroyuki Murakami, Seth Underwood, and James Kossin. "Projected Response of Tropical Cyclone Intensity and Intensification in a Global Climate Model." *Journal of Climate* 31, no. 20 (October 15, 2018): 8281–8303. https://doi.org/10.1175/JCLI-D-17-0898.1.

Bhusal, Narayan, Mukesh Gautam, Michael Abdelmalak, and Mohammed Benidris. "Modeling of Natural Disasters and Extreme Events for Power System Resilience Enhancement and Evaluation Methods." In *2020 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*, 1–6, 2020. https://doi.org/10.1109/PMAPS47429.2020.9183679.

Bostick, T.P., E.B. Connelly, J.H. Lambert, and I. Linkov. “Resilience Science, Policy and Investment for Civil Infrastructure.” *Reliability Engineering & System Safety* 175 (July 2018): 19–23. https://doi.org/10.1016/j.ress.2018.02.025.

Cai, Yongyang, Kenneth L. Judd, Timothy M. Lenton, Thomas S. Lontzek, and Daiju Narita. “Environmental Tipping Points Significantly Affect the Cost−benefit Assessment of Climate Policies.” *Proceedings of the National Academy of Sciences* 112, no. 15 (April 14, 2015): 4606–11. https://doi.org/10.1073/pnas.1503890112.

Cheng, Linyin, and Amir AghaKouchak. “Nonstationary Precipitation Intensity-Duration-Frequency Curves for Infrastructure Design in a Changing Climate.” *Scientific Reports* 4, no. 1 (November 18, 2014): 7093. https://doi.org/10.1038/srep07093.

Church, John A., and Neil J. White. “Sea-Level Rise from the Late 19th to the Early 21st Century.” *Surveys in Geophysics* 32, no. 4–5 (September 2011): 585–602. https://doi.org/10.1007/s10712-011-9119-1.

Colgan, Charles S., "Financing Natural Infrastructure for Coastal Flood Damage Reduction" (2017).Climate Change. 8. https://digitalcommons.usm.maine.edu/climatechange/8

Contento, Alessandro, Hao Xu, and Paolo Gardoni. “Chapter Two - Risk Analysis for Hurricanes Accounting for the Effects of Climate Change.” In *Climate Adaptation Engineering*, edited by Emilio Bastidas-Arteaga and Mark G. Stewar, 39–72. Butterworth-Heinemann, 2019. https://doi.org/10.1016/B978-0-12-816782-3.00002-4.

CRS. “Bay County Is Highly Prone to Flood Hazards Associated with Hurricanes, Tropical Storms, and Rainfall with High Intensity or Duration,” 2019, 13.

CRS. “Harbor Dredging: Issues and Historical Funding.” Accessed February 16, 2022. https://www.everycrsreport.com/reports/IN11133.html.

Cutter, Susan L., and Sahar Derakhshan. “Temporal and Spatial Change in Disaster Resilience in US Counties, 2010–2015.” *Environmental Hazards* 19, no. 1 (January 1, 2020): 10–29. https://doi.org/10.1080/17477891.2018.1511405.

Department of Defense, Office of the Undersecretary of Defense (Acquisition and Sustainment). “Department of Defense 2021 Climate Adaptation Plan,” September 1, 2021, 32.

Department of Economic and Social Affairs. "World Economic and Social Survey 2016: Climate Change Resilience: An Opportunity for Reducing Inequalities | Department of Economic and Social Affairs." Accessed December 29, 2021. https://www.un.org/development/desa/dpad/publication/world-economic-and-social-survey-2016-climate-change-resilience-an-opportunity-for-reducing-inequalities/.

Dugan, JE. "Estuarine and Coastal Structures: Environmental Effects, A Focus on Shore and Nearshore Structures." Elsevier, 2011. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.461.4762&rep=rep1&type=pdf.

Edney, Mary Margaret. "Using Natural Infrastructure to Increase Resilience for Military Installations." U.S. Army Corps of Engineers Headquarters, September 9, 2020. https://www.usace.army.mil/Media/News/NewsSearch/Article/2341988/using-natural-infrastructure-to-increase-resilience-for-military-installations/.

Elko, Nicole, Tiffany Roberts Briggs, Lindino Benedet, Quin Robertson, Gordon Thomson, Bret M. Webb, and Kimberly Garvey. "A Century of U.S. Beach Nourishment." *Ocean & Coastal Management* 199 (January 1, 2021): 105406. https://doi.org/10.1016/j.ocecoaman.2020.105406.

Elliott, M., and A. K. Whitfield. "Challenging Paradigms in Estuarine Ecology and Management." *Estuarine, Coastal and Shelf Science* 94, no. 4 (October 20, 2011): 306–14. https://doi.org/10.1016/j.ecss.2011.06.016.

Emanuel, Kerry. "Assessing the Present and Future Probability of Hurricane Harvey's Rainfall." *Proceedings of the National Academy of Sciences* 114, no. 48 (November 28, 2017): 12681–84. https://doi.org/10.1073/pnas.1716222114.

EO 14008, "Executive Order on Tackling the Climate Crisis at Home and Abroad." The White House, February 2, 2021. https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad

EO 140157. "Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability." The White House, December 8, 2021. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/12/08/executive-order-on-catalyzing-clean-energy-industries-and-jobs-through-federal-sustainability/.

Fischer, E. M., S. Sippel, and R. Knutti. “Increasing Probability of Record-Shattering Climate Extremes.” *Nature Climate Change* 11, no. 8 (August 2021): 689–95. https://doi.org/10.1038/s41558-021-01092-9.

Fraza, Erik, and James B. Elsner. “A Spatial Climatology of North Atlantic Hurricane Intensity Change.” *International Journal of Climatology* 34, no. 9 (2014): 2918–24. https://doi.org/10.1002/joc.3884.

Frazier, Tim G., Nathan Wood, Brent Yarnal, and Denise H. Bauer. “Influence of Potential Sea Level Rise on Societal Vulnerability to Hurricane Storm-Surge Hazards, Sarasota County, Florida.” *Applied Geography*, Climate Change and Applied Geography – Place, Policy, and Practice, 30, no. 4 (December 1, 2010): 490–505. https://doi.org/10.1016/j.apgeog.2010.05.005.

Ghimire, Ekaraj, and Suresh Sharma. “Flood Damage Assessment in HAZUS Using Various Resolution of Data and One-Dimensional and Two-Dimensional HEC-RAS Depth Grids.” *Natural Hazards Review* 22, no. 1 (February 2021): 04020054. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000430.

Gittman, Rachel K., F. Joel Fodrie, Alyssa M. Popowich, Danielle A. Keller, John F. Bruno, Carolyn A. Currin, Charles H. Peterson, and Michael F. Piehler. “Engineering Away Our Natural Defenses: An Analysis of Shoreline Hardening in the US.” *Frontiers in Ecology and the Environment* 13, no. 6 (2015): 301–7. https://doi.org/10.1890/150065.

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

Grabowski, Jonathan H., Robert D. Brumbaugh, Robert F. Conrad, Andrew G. Keeler, James J. Opaluch, Charles H. Peterson, Michael F. Piehler, Sean P. Powers, and Ashley R. Smyth. “Economic Valuation of Ecosystem Services Provided by Oyster Reefs.” *BioScience* 62, no. 10 (October 1, 2012): 900–909. https://doi.org/10.1525/bio.2012.62.10.10.

Habel, Shellie, Charles H. Fletcher, Matthew Barbee, and Tiffany R. Anderson. “The Influence of Seasonal Patterns on a Beach Nourishment Project in a Complex Reef Environment.” *Coastal Engineering* 116 (October 1, 2016): 67–76. https://doi.org/10.1016/j.coastaleng.2016.06.006.

Hall, Timothy M., and James P. Kossin. “Hurricane Stalling along the North American Coast and Implications for Rainfall.” *Npj Climate and Atmospheric Science* 2, no. 1 (June 3, 2019): 1–9. https://doi.org/10.1038/s41612-019-0074-8.

Hauser, Samantha, Marcia S. Meixler, and Magdeline Laba. "Quantification of Impacts and Ecosystem Services Loss in New Jersey Coastal Wetlands Due to Hurricane Sandy Storm Surge." *Wetlands* 35, no. 6 (December 1, 2015): 1137–48. https://doi.org/10.1007/s13157-015-0701-z.

Heerden, Ivor Ll. van. "The Failure of the New Orleans Levee System Following Hurricane Katrina and the Pathway Forward." *Public Administration Review* 67 (2007): 24–35.

Hil, Greg. "Better Management Through Measurement: Integrating Archaeological Site Features into a GIS-Based Erosion and Sea Level Rise Impact Assessment—Blueskin Bay, New Zealand." *The Journal of Island and Coastal Archaeology* 15, no. 1 (January 2, 2020): 104–26. https://doi.org/10.1080/15564894.2018.1531331.

Hinkel, Jochen, Daniel Lincke, Athanasios T. Vafeidis, Mahé Perrette, Robert James Nicholls, Richard S. J. Tol, Ben Marzeion, Xavier Fettweis, Cezar Ionescu, and Anders Levermann. "Coastal Flood Damage and Adaptation Costs under 21st Century Sea-Level Rise." *Proceedings of the National Academy of Sciences of the United States of America* 111, no. 9 (March 4, 2014): 3292–97. https://doi.org/10.1073/pnas.1222469111.

H.R. 302 - 115th Congress (2017-2018): "Disaster Recovery Reform Act of 2018 | FEMA.Gov." Accessed January 17, 2022. https://www.fema.gov/disaster/disaster-recovery-reform-act-2018.

Karamouz, Mohammad, Mohammad Fereshtehpour, Forough Ahmadvand, and Zahra Zahmatkesh. "Coastal Flood Damage Estimator: An Alternative to FEMA's HAZUS Platform." *Journal of Irrigation and Drainage Engineering* 142, no. 6 (June 1, 2016): 04016016. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001017.

Kossin, James P., Kenneth R. Knapp, Timothy L. Olander, and Christopher S. Velden. "Global Increase in Major Tropical Cyclone Exceedance Probability over the Past Four Decades." *Proceedings of the National Academy of Sciences* 117, no. 22 (June 2, 2020): 11975–80. https://doi.org/10.1073/pnas.1920849117.

Lathrop, Richard, Lisa Auermuller, James Trimble, and John Bognar. "The Application of WebGIS Tools for Visualizing Coastal Flooding Vulnerability and Planning for Resiliency: The New Jersey Experience." *ISPRS International Journal of Geo-Information* 3, no. 2 (June 2014): 408–29. https://doi.org/10.3390/ijgi3020408.

McLusky, Donald, and Michael Elliott. *The Estuarine Ecosystem. Ecology, Threats and Management*, 2004. https://doi.org/10.1093/acprof:oso/9780198525080.001.0001.

Miller, et al., Brandon. “Hurricanes Are Becoming More Dangerous. Here’s Why.” Accessed August 31, 2021. https://www.cnn.com/interactive/2020/12/us/hurricanes-climate-change/.

Moore. “Complexities in Barrier Island Response to Sea Level Rise: Insights from Numerical Model Experiments, North Carolina Outer Banks - Moore - 2010 - Journal of Geophysical Research: Earth Surface - Wiley Online Library,” 2010. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2009JF001299.

Morris, Rebecca L., Teresa M. Konlechner, Marco Ghisalberti, and Stephen E. Swearer. “From Grey to Green: Efficacy of Eco-Engineering Solutions for Nature-Based Coastal Defence.” *Global Change Biology* 24, no. 5 (May 2018): 1827–42. https://doi.org/10.1111/gcb.14063.

Morrow, Ashley. “No Major U.S. Hurricane Landfalls in Nine Years: Luck?” Text. NASA, May 13, 2015. http://www.nasa.gov/feature/goddard/no-major-us-hurricane-landfalls-in-nine-years-luck.

Nastev, Miroslav, and Nikolay Todorov. “Hazus: A Standardized Methodology for Flood Risk Assessment in Canada.” *Canadian Water Resources Journal* 38, no. 3 (September 2013): 223–31. https://doi.org/10.1080/07011784.2013.801599.

National Oceanic and Atmospheric Administration. “Record-Breaking Atlantic Hurricane Season Draws to an End | National Oceanic and Atmospheric Administration.” Accessed January 7, 2022. https://www.noaa.gov/media-release/record-breaking-atlantic-hurricane-season-draws-to-end.

National Oceanic and Atmospheric Administration. “Socioeconomic Data Summary,” n.d., 2.

Office of Coastal Management. “Hurricane Costs.” Accessed January 7, 2022. https://coast.noaa.gov/states/fast-facts/hurricane-costs.html.

Office of Ocean & Coastal Resource Management. “National Coastal Program Dredging Policies,” Accessed 12/2021. 320.

Office of The Deputy Assistant Secretary of Defense For Environment and Energy Resilience. “DOD Efforts Showcased in Climate Adaptation Companion Document.” U.S. Department of Defense. Accessed December 31, 2021. https://www.defense.gov/News/News-Stories/Article/Article/2832914/dod-efforts-showcased-in-climate-adaptation-companion-document/.

Oost, A. P., P. Hoekstra, A. Wiersma, B. Flemming, E. J. Lammerts, M. Pejrup, J. Hofstede, et al. “Barrier Island Management: Lessons from the Past and Directions for the Future.” *Ocean & Coastal Management*, Special Issue on the Wadden Sea Region, 68 (November 1, 2012): 18–38. https://doi.org/10.1016/j.ocecoaman.2012.07.010.

Pinson, A.O., K.D. White, E.E. Ritchie, H.M. Conners, and J.R. Arnold. (2021). DoD Installation Exposure to Climate Change at Home and Abroad. U.S. Army Corps of Engineers: Washington, DC

Rao, Nalini, Andrea Ghermandi, Rosimeiry Portela, and Xuanwen Wang. “Global Values of Coastal Ecosystem Services: A Spatial Economic Analysis of Shoreline Protection Values.” *Ecosystem Services* 11 (January 22, 2015). https://doi.org/10.1016/j.ecoser.2014.11.011.

Reguero, Borja G., Michael W. Beck, David N. Bresch, Juliano Calil, and Imen Meliane. “Comparing the Cost Effectiveness of Nature-Based and Coastal Adaptation: A Case Study from the Gulf Coast of the United States.” *PLOS ONE* 13, no. 4 (April 11, 2018): e0192132. https://doi.org/10.1371/journal.pone.0192132.

Rød, Bjarte, David Lange, Marianthi Theocharidou, and Christer Pursiainen. “From Risk Management to Resilience Management in Critical Infrastructure.” *Journal of Management in Engineering* 36, no. 4 (July 1, 2020): 04020039. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000795.

Rodysill, Jessica R., Jeffrey P. Donnelly, Richard Sullivan, Philip D. Lane, Michael Toomey, Jonathan D. Woodruff, Andrea D. Hawkes, et al. “Historically Unprecedented Northern Gulf of Mexico Hurricane Activity from 650 to 1250 CE.” *Scientific Reports* 10, no. 1 (November 5, 2020): 19092. https://doi.org/10.1038/s41598-020-75874-0.

Santos, Víctor M., Mercè Casas-Prat, Benjamin Poschlod, Elisa Ragno, Bart van den Hurk, Zengchao Hao, Tímea Kalmár, Lianhua Zhu, and Husain Najafi. “Statistical Modelling and Climate Variability of Compound Surge and Precipitation Events in a Managed Water System: A Case Study in the Netherlands.” *Hydrology and Earth System Sciences* 25, no. 6 (June 24, 2021): 3595–3615. https://doi.org/10.5194/hess-25-3595-2021.

Shafiee-Jood, Majid, Ximing Cai, Ligang Chen, Xin-Zhong Liang, and Praveen Kumar. “Assessing the Value of Seasonal Climate Forecast Information through an End-to-End Forecasting Framework: Application to U.S. 2012 Drought in Central Illinois.” *Water Resources Research* 50, no. 8 (2014): 6592–6609. https://doi.org/10.1002/2014WR015822.

Shi, Linda, and Varuzzo, Andrew. “Surging Seas, Rising Fiscal Stress: Exploring Municipal Fiscal Vulnerability to Climate Change - ScienceDirect.” Accessed November 4, 2021. https://www.sciencedirect.com/science/article/pii/S0264275118314100.

Sutton-Grier, Ariana E., Kateryna Wowk, and Holly Bamford. “Future of Our Coasts: The Potential for Natural and Hybrid Infrastructure to Enhance the Resilience of Our Coastal Communities, Economies and Ecosystems.” *Environmental Science & Policy* 51 (August 1, 2015): 137–48. https://doi.org/10.1016/j.envsci.2015.04.006.

Tyndall Program Management Office. “Tyndall AFB | Installation of the Future.” Accessed August 31, 2021. https://www.tyndallifs.com/index.php.

U. S. Government Accountability Office. “Climate Resilience: A Strategic Investment Approach for High-Priority Projects Could Help Target Federal Resources.” Accessed February 18, 2022. https://www.gao.gov/products/gao-20-127.

U. S. Government Accountability Office. “Climate Resilience: DOD Needs to Assess Risk and Provide Guidance on Use of Climate Projections in Installation Master Plans and Facilities Designs,” no. GAO-19-453 (June 12, 2019). https://www.gao.gov/products/GAO-19-453.

U.S. Government Accountability Office. “Army Corps of Engineers: Factors Contributing to Cost Increases and Schedule Delays in the Olmsted Locks and Dam Project | U.S. GAO.” Accessed February 18, 2022. https://www.gao.gov/products/gao-17-147.

U.S. Department of Commerce. “State, Territory, and Commonwealth Beach Nourishment Programs,” Accessed 12/2021., 118.

US Department of Commerce, NOAA. “NWS JetStream - Tropical Cyclone Hazards.” NOAA’s National Weather Service. Accessed January 7, 2022. https://www.weather.gov/jetstream/tc_hazards.

US EPA, Region 9. “San Francisco Bay Long Term Management Strategy for Dredging (LTMS) - Region 9 - EPA.” Accessed December 30, 2021. https://19january2017snapshot.epa.gov/www3/region9/water/dredging/ltms/index.html.

Wagner, Melissa, Netra Chhetri, and Melanie Sturm. “Adaptive Capacity in Light of Hurricane Sandy: The Need for Policy Engagement.” *Applied Geography* 50 (June 1, 2014): 15–23. https://doi.org/10.1016/j.apgeog.2014.01.009.

Warns, Steve. “REPI Challenge Yields More than $24M for AF Installations.” Air Force, 2021. https://www.af.mil/News/Article-Display/Article/2698558/repi-challenge-yields-more-than-24m-for-af-installations/.

Wesenbeeck, Bregje K. van, Jan P. M. Mulder, Marcel Marchand, Denise J. Reed, Mindert B. de Vries, Huib J. de Vriend, and Peter M. J. Herman. “Damming Deltas: A Practice of the Past? Towards Nature-Based Flood Defenses.” *Estuarine, Coastal and Shelf Science* 140 (March 1, 2014): 1–6. https://doi.org/10.1016/j.ecss.2013.12.031.

Winsemius, H. C., E. Dutra, F. A. Engelbrecht, E. Archer Van Garderen, F. Wetterhall, F. Pappenberger, and M. G. F. Werner. “The Potential Value of Seasonal Forecasts in a Changing Climate in Southern Africa.” *Hydrology and Earth System Sciences* 18, no. 4 (April 25, 2014): 1525–38. https://doi.org/10.5194/hess-18-1525-2014.

Woods, David D. “Four Concepts for Resilience and the Implications for the Future of Resilience Engineering.” *Reliability Engineering & System Safety*, Special Issue on Resilience Engineering, 141 (September 1, 2015): 5–9. https://doi.org/10.1016/j.ress.2015.03.018.

Ysebaert, Tom, Dirk-Jan van der Hoek, Rick Wortelboer, Jeroen W. M. Wijsman, Marijn Tangelder, and Arno Nolte. “Management Options for Restoring Estuarine Dynamics and Implications for Ecosystems: A Quantitative Approach for the Southwest Delta in the Netherlands.” *Ocean & Coastal Management* 121 (March 1, 2016): 33–48. https://doi.org/10.1016/j.ocecoaman.2015.11.005.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 074-0188*

1. REPORT DATE *(DD-MM-YYYY)* 25-03-2022	**2. REPORT TYPE** Master’s Thesis	**3. DATES COVERED** *(From – To)* September 2020 – March 2022

TITLE AND SUBTITLE NATURAL INFRASTRUCTURE ALTERNATIVES MITIGATE HURRICANE-DRIVEN FLOOD VULNERABILITY: APPLICATION TO TYNDALL AIR FORCE BASE	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Vance, Kiara L., Captain, USAF	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/ENY) 2950 Hobson Way, Building 640 WPAFB OH 45433-8865	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT-ENV-MS-22-M-268
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Civil Engineering Center 2261 Hughes Ave, Ste.155 JBSA Lackland, TX 78236-9853	**10. SPONSOR/MONITOR’S ACRONYM(S)** **AFCEC**
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRUBTION STATEMENT A. APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES
This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

14. ABSTRACT

Hurricane frequency and magnitude intensification are expected over the remainder of the twenty-first century. Uncertainty in future projections requires that coastal communities approach adaptation decisions with caution. Traditional approaches are costly and inflexible. Soft policy adaptations are largely unenforceable. Hard, natural adaptations have emerged as an opportunity to partially mitigate the growing risk of extreme flooding, without the large investments required for traditional approaches, where natural infrastructure already exists. Existing literature for natural adaptations has not leveraged intensification expectations for hurricane events. This research uses multi-hazard damage evaluation software and spatial analysis to investigate placement of dredged sediment as a barrier island maintenance technique to determine economic viability, as compared to no-action alternatives. The efficacy of this strategy is tested against 18 threat and time calibrated scenarios, applied to existing barrier islands at Tyndall AFB. The results illustrate that protection of 7 square miles of existing barrier islands could help avert facility and infrastructure damage from high-intensity hurricane surge events predicted at 2100 by up to 3 orders of magnitude compared to a status quo scenario. The broader implications suggest that planners should look to preserve natural infrastructure that provides surge protection based on the ability to mitigate damages from intensified climate factors.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Lt Col Justin D. Delorit, AFIT/ENV
U	U	U	UU	74	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-3636, ext. 4826 (justin.delorit@afit.edu)

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18