GUIDELINES FOR EVALUATING WAVE REDUCTION LOSS IN SALT MARSHES AND APPLICATION TO CONDITION ASSESSMENT

by

ANASTASIA N. KLOSTERMAN

(Under the Direction of C. Brock Woodson)

ABSTRACT

Coastal infrastructure in the form of seawalls and salt marshes is essential for the success of the economy, society, and environment. Such infrastructure (both natural and constructed) around the world enables trade, connects communities, creates opportunities, and protects from the unpredictable natural environment. Without reliable coastal infrastructure, our nation would not be what it is today, which is why these assets need to be upheld and protected through efficient asset management and monitoring. Unlike sea walls and other gray infrastructure, there is no well-established monitoring method for salt marshes in the context of asset management. In this thesis, I evaluate current monitoring methods for gray infrastructure and salt marshes. I use measured salt marsh erosion rates over time in order to develop guidelines for monitoring wave reduction in salt marsh habitats. Salt marsh erosion rates were compared over the years utilizing different environmental thresholds and variations to ensure a conservative approach to monitoring over time. The proposed approach is derived from current asset management approaches for monitoring gray infrastructure. The intent of using an asset management approach was to ensure that the proposed monitoring method fits into universal standards of current infrastructure assessment, in the form of a rating scale. Based on this evidence, a condition assessment rating and maintenance plan for salt marshes is proposed along with recommended remediation methods and hybrid infrastructure plans.

INDEX WORDS: monitoring, salt marsh, natural infrastructure, asset management, erosion rates, erosion

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INTRODUCTION AND MOTIVATION

Salt marshes are crucial to environmental health. These complex ecosystems filter water pollutants and nutrients, encourage biodiversity, provide community protection from harsh storms and rising sea levels, host a supportive breeding ground for commercially valuable fish, create a foundation for the marine food web, and offer recreational opportunities (Phan, n.d.). Although salt marshes are an asset to coastal communities, the National Oceanic and Atmospheric Administration (NOAA) estimates that the United States of America (US) loses roughly 80,000 acres of coastal wetlands and salt marshes each year. The primary source of this loss being coastal development and rising sea-level, which can drown the marshes where there isn't proper undeveloped area to allow for marsh migration (NOAA, 2021). Salt marshes, as a component of natural infrastructure, are a necessary asset to protect yet there is no structured monitoring or management process currently in place to do so.

Infrastructure can take many forms – from bridges connecting cities separated by water to salt marshes protecting coastal communities from floods – but all types of infrastructure require a monitoring plan to ensure proper performance and longevity. Using engineering judgment and collected data, it is important to make smart and timely decisions about the maintenance, repair, and rehabilitation of both natural and gray infrastructure. Without proper monitoring and asset management plans, proper decisions cannot be made, which can lead to large and sometimes detrimental mistakes that cost taxpayers money and valuable resources.

This research utilized existing gray infrastructure asset management practices and current structural rating systems in the US as a baseline for a proposed asset management approach for salt marshes as natural infrastructure. This research assesses typical salt marsh erosion rates in different locations around the US to develop a similar condition assessment with respect to wave reduction capabilities of salt marshes. The three objectives of this research are to:

1. Understand the current asset management approach utilized when monitoring gray and natural infrastructure,
2. Develop a statistical wave reduction model based on erosion rates,
3. Use the wave reduction model to formulate a condition assessment that can be applied to salt marshes.

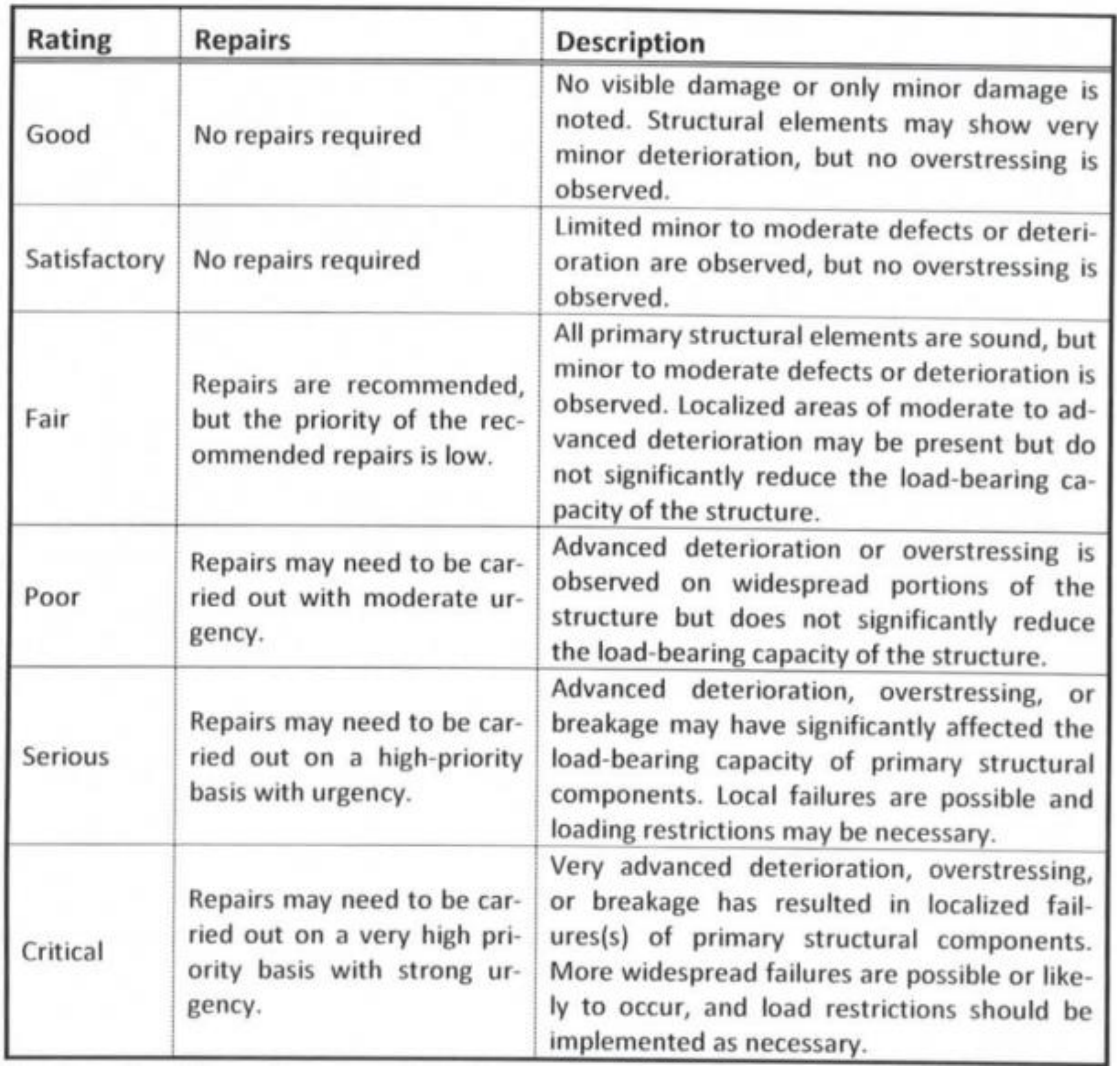
The overall results, conclusions, recommendations, and future plans for this research are discussed within this thesis.

1.1 Current Monitoring Methods

Gray infrastructure often utilizes an asset management approach that is not currently applied to the monitoring of natural infrastructure. Seawalls and bulkheads, like most gray infrastructure, are currently monitored and placed on a priority scale based on a structural grade given during a risk assessment (MW Engineering, Inc., n.d.). A risk assessment determines the overall risk based on the probability and consequence of a failure event. To estimate the level of risk and grade the consequences, probability of failure of the asset, and the probability of the event occurring should all be determined (ACS Institute, n.d.). Once observed and scored, gray infrastructure is given a rating ranging from "Good" to "Critical" depending on the visible damage and deterioration of the structure (ASCE, 2001) (*Figure 1.1*).

For example, seawalls have a predicted useful life of 35 years and are given a "Good" rating in their best condition, meaning they are fit for their purpose and are typically in excellent condition (ESP, 2015). A "Satisfactory" rating is given to sea wall structures that have roughly 21-30 years of life remaining, and are adequate for now, possibly showing some signs of general deterioration but are still safe and reliable (Cummins Cederberg, Inc., 2019). A "Fair" rating is given to sea walls that have about 16-20 years of life remaining, and typically represents infrastructure in a mediocre state that requires attention. Sea walls in fair condition show general signs of deterioration, and some elements exhibit significant deficiencies that increase risk (Cummins Cederberg, Inc., 2019). "Poor" rated sea walls have 11-15 years remaining and is typically below standard with many elements approaching the end of their service life (Cummins Cederberg, Inc., 2019). Sea walls with a "Serious" rating have 6-10 years remaining and is a serious concern with a strong risk of failure (Cummins Cederberg, Inc., 2019). "Critical" is the most immediate condition with 0-5 years of life remaining. Critical rated sea walls are in unacceptable condition with widespread advance signs of deterioration where many of the components of the system exhibit signs of imminent failure (Cummins Cederberg, Inc., 2019). Seawalls that receive a Critical rating trigger an immediate repair response from governments or other entities, while the other ratings provide a priority for repair based on available budget.

Like seawalls and other waterfront infrastructure, the routine condition assessment ratings are utilized when determining bulkhead health and condition (Dredging and Marine Consultants, LLC., 2016). Bulkheads have a predicted useful life of 20-50 years depending on the materials used. Given different materials, exposure, and function, the years associated with the assessment rating scale will not be the same for all types of gray infrastructure. While the life expectancy of the rated infrastructure may be different between sea walls and bulkheads, the given rating based on deterioration or risk is the same. For example, a bulkhead in serious condition exhibits severe cracking and is labeled as a serious concern with a strong risk of failure just as it would be for a sea wall (Dredging and Marine Consultants, LLC., 2016).



Rating	Repairs	Description
Good	No repairs required	No visible damage or only minor damage is noted. Structural elements may show very minor deterioration, but no overstressing is observed.
Satisfactory	No repairs required	Limited minor to moderate defects or deterioration are observed, but no overstressing is observed.
Fair	Repairs are recommended, but the priority of the recommended repairs is low.	All primary structural elements are sound, but minor to moderate defects or deterioration is observed. Localized areas of moderate to advanced deterioration may be present but do not significantly reduce the load-bearing capacity of the structure.
Poor	Repairs may need to be carried out with moderate urgency.	Advanced deterioration or overstressing is observed on widespread portions of the structure but does not significantly reduce the load-bearing capacity of the structure.
Serious	Repairs may need to be carried out on a high-priority basis with urgency.	Advanced deterioration, overstressing, or breakage may have significantly affected the load-bearing capacity of primary structural components. Local failures are possible and loading restrictions may be necessary.
Critical	Repairs may need to be carried out on a very high priority basis with strong urgency.	Very advanced deterioration, overstressing, or breakage has resulted in localized failures(s) of primary structural components. More widespread failures are possible or likely to occur, and load restrictions should be implemented as necessary.

Figure 1.1: Routine Condition Assessment Ratings by the American Society of Civil Engineers (ASCE) Table 2-4. From Routine Underwater Condition Assessment Ratings, Page 21, Underwater Investigations Standard Practice Manual, as published in the ASCE Manuals and Reports on Engineering Practice No.101, Copyright 2001 (Childs, 2001)

The recommended maintenance plan for seawalls and bulkheads requires routine monitoring. Biennial visual inspections are recommended, with annual inspections reserved for the more severely deteriorated and critical locations (Geeley and Hansen, 2014). Some locations may need more in-depth underwater inspection as structures may appear more structurally sound above water than below. Once these inspections are complete each structure is given a rating to summarize the physical condition and health. Inspection results are organized by updating the inspection reports, ratings, and documenting changed conditions (Geeley and Hansen, 2014).

Monitoring is also important for structured decision-making and adaptive management which involves identifying management objectives, alternative actions, and expected outcomes for natural infrastructure projects. Constructed salt marshes and reefs are monitored more on a project-to-project basis with varying structures and objectives, whereas natural reefs and marshes may not be monitored at all as infrastructure (Doick, n.d.). Depending on the type of natural infrastructure, field acceptance testing, and performance baseline testing must be completed within 60 days of construction. Ongoing field performance testing must be performed no less than once every five years (Green Infrastructure Monitoring Plan, 2021). This performance baseline and monitoring requirement includes surveys that are more community-focused including reports on social, economic, and environmental benefits (Green Infrastructure Monitoring Plan, 2021). Due to the only recent interest in natural infrastructure, the monitoring methods are often more research-based and much less universal compared to the developed gray infrastructure methods.

To improve overall condition of integrated infrastructure systems, a more universal monitoring method structure is recommended since seawalls and salt marshes do not act in isolation, but as an integrated hazard protection system. Seawalls, bulkheads, salt marshes, and reefs should be monitored on a similar scale so they can be compared and managed effectively.

Utilizing a common monitoring method would make it easier to integrate and assess these infrastructure components together moving forward. Therefore, a priority scale based on a structural grade framework needs to be created and applied for natural infrastructure assets. I propose that like seawalls and other gray infrastructure, salt marshes and natural infrastructure should be given a rating ranging from "Good" to "Critical", based on their life expectancy and need for rehabilitation. However, life expectancy for salt marshes is almost impossible to quantify and should be perpetual, therefore I quantify the time over which certain thresholds of protection are lost.

As natural infrastructure is not a replacement for gray infrastructure and vice versa – there will always be a need for both. To adapt to the escalating impact of climate change and breakdown, especially on the coastlines facing sea-level rise and stronger storms, there must be a change in current infrastructure approaches and methods. Applying natural-gray hybrid solutions to reduce coastal hazards is the most flexible and cost-effective option to reduce flooding and protect shorelines (Sutton-Grier et all, 2015). Preserving or developing salt marshes in front of seawalls to act as a wave buffer to minimize damage to sea walls allows utilization of the strengths of both natural and gray infrastructure types for enhanced coastal protection (Conservation International, n.d.).

For example, as sea levels continuously rise, the threat of flooding along the North Brazil Shelf shorelines is constantly growing. Coastal resilience along the North Brazil Shelf has been improved by plans to utilize natural-gray infrastructure (Conservation International, n.d.). Conservation International is partnering with the Guyana government to develop natural-gray infrastructure by restoring mangrove forests and reinforcing seawalls planned in strategic areas. By utilizing both natural and gray infrastructure, they will be able to reduce the risk of flooding and improve resilience to the effects of climate change. The plan reported a potential $1.5-$3.6 billion cost savings by replacing aging seawalls with mangrove belts or a combination of mangrove belts and repaired sea walls (Conservation International, n.d.). Saving the mangroves will not only save on infrastructure investment cost but will also increase their annual fisheries earnings by almost $544,320 (Conservation International, n.d.).

The US Army Corps of Engineers (USACE) and the National Oceanic and Atmospheric Administration (NOAA) recognize the value of a hybrid infrastructure approach to improve social, economic, and ecosystem resilience. These hybrid solutions include "living shoreline" approaches that integrate living components, such as plantings, with structural techniques, such as seawalls or breakwaters (SAGE, 2015). These organizations also list many benefits for hybrid approaches such as erosion control and shore stabilization, restored and enhanced habitat which supports fish and wildlife populations, enhanced community enjoyment, opportunities for education, and improved water quality from settling or trapping sediment. There are also challenges listed that correspond with the current monitoring methods: not all techniques have the same level of performance or success monitoring, and less practiced techniques may require more monitoring (SAGE, 2015).

The cons listed by USACE and NOAA provide a clear need for a monitoring plan for natural infrastructure that is inspired by the current gray infrastructure approach. Monitoring and managing natural and gray infrastructure on similar scales and with a similar asset management approach will make project transition and project planning smoother when natural-gray hybrid projects become more common. Not only will hybrid infrastructure be more successful but there would also be more education and understanding as well as less monitoring required overtime for natural infrastructure projects. My proposed monitoring method is just the first step towards ensuring infrastructure continues to be an asset that supports the growing economy, diverse society, and changing environment.

1.2 Defining Asset Management

An asset is defined as something that provides current, future, or potential economic benefit for an individual or other entity. Asset management is defined by the International Organization for Standardization (ISO) as “the financial, operational, maintenance, risk, and other related activities of an organization to realize more value from its assets” (ISO, 2019). When using the asset management approach to manage infrastructure, an asset management plan is created to ensure budget and employee personnel are used efficiently and effectively in the maintenance and monitoring of infrastructure components (assets).

Asset management involving infrastructure is typically a management method utilized and entrusted to government entities. Asset management in terms of infrastructure is known as sustaining public infrastructure assets such as bridges, ports, transit systems, railways, wastewater systems, and seawalls given a specified budget. The asset management approach tends to focus on the maintenance, rehabilitation, and replacement of infrastructure with the end goal being the extension of that infrastructures service life. This is an ongoing process of maintaining, upgrading, and operating physical assets cost-effectively, based on a continuous inventory and condition assessment.

1.3 Importance of Asset Management

Asset management is an important and necessary process that helps provide a clearer picture of the current condition of state and local infrastructure. This process can help governments and asset owners make more informed decisions about asset operations, maintenance, and renewal. State and local municipal infrastructure is important as it is a service many residents and communities rely on, so they are assets that must be protected. Asset management planning provides information about full life cycle costs of owning and operating existing and future infrastructure, levels of service (LOS), risk and how those risks are managed, and implications of future demands. Without asset management it is hard to ensure safe and effective municipal infrastructure.

Figure 1.2: Asset Management Plan Process Example (NCDOT)

1.4 Life Cycle Assessment

Life cycle assessment (LCA) is a framework for analyzing the potential environmental performance of a product or service. This process includes all stages in the life of a product including material extraction, manufacturing, use and disposal. LCA involves defining the goal and scope of the study, collecting the needed data for all life cycle stages, assembling a life cycle inventory, calculating impacts using life cycle impact assessment methods, iteratively verifying and improving the results, and providing a proper interpretation. LCA is particularly valuable for comparing various alternative products or systems that provide the same purpose.

1.5 Thesis Components and Structure

The structure of this thesis includes five chapters that explain the proposed monitoring method for salt marshes and how to determine when and how frequently monitoring should be done. Chapter 2 presents the background and literature reviews of current monitoring methods and case studies providing supporting information of the importance of salt marshes. Chapter 3 presents the methods to determine how often monitoring should be done based on observed marsh erosion/subsidence rates. Research results are discussed in Chapter 4. Conclusions, recommendations, and future research opportunities are resolved in Chapter 5.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Natural Infrastructure as Flood and Erosion Protection

Climate change is having a huge impact on coastal shores and communities. Climate change alone has been deemed responsible for glacier melting, rise in global sea levels, and an increase in extreme weather event frequency and brutality (US EPA, n.d.). A major consequence of these issues is the increased severity and frequency of flooding across the world. Other nations such as the United Kingdom (UK) have already begun to turn to natural infrastructure to mitigate this coastal issue (Grantham Institute, 2019). At the moment, the UK's approach to installing flood defenses is by utilizing gray infrastructure, such as sea walls and boulder barriers (Grantham Institute, 2019). However, this approach is very expensive and static (cannot evolve with conditions), and therefore not appealing which is why they have turned to dynamic nature-based solutions to prevent coastal flooding.

Nature-based solutions, or natural infrastructure, involve the management and use of natural resources to resolve challenges, such as flooding (The Nature Conservancy, 2020). Sand dunes, mudflats and saltmarshes are all effective infrastructure methods to protect the coast from flood and erosion. They do this by decreasing the ocean's wave energy near the coast and on land, as well as absorbing excess rainwater during time of heavy and intense rain (Grantham Institute, 2019). The UK reports that salt marshes have reduced wave height up to 80% and have effectively prevented soil erosion, making salt marshes a prime solution to coastal flooding and erosion (Möller, 2014).

Salt marshes are key to reducing coastal erosion and flooding but are also subject to flooding and scour themselves. While coastal marshes naturally adapt to sea-level rise by migrating inland through a process called transgression, coastal structures and the speed of sea-level rise can hinder this natural process (Bouma et al, 2009). Scour also impacts the natural process of a salt marsh, influencing if it will extend laterally or retreat. High hydrodynamic energy, either from waves or tidal currents, will generally cause salt marsh ecosystems to reduce in size due to erosion. Once the salt marshes are eroded and change to a bare mudflat, it takes a long time to re-establish the salt marsh environment (Bouma et al, 2009).

Another perk to utilizing this form of natural infrastructure is that salt marshes sequester large quantities of carbon which is helpful in terms of the climate crisis. These types of habitats are known as “carbon sinks” as they contain large stores of carbon accumulated over thousands of years (NOAA, 2021). The carbon captured by the world’s ocean and coastal ecosystems is referred to as “blue carbon” and this carbon can be released by these systems when they are damaged (US Department of Commerce, NOAA, 2013). Therefore, protecting and utilizing these coastal habitats will reduce the carbon footprint all while protecting coastal shorelines.

2.2 Wave Attenuation over Coastal Salt Marshes Under Storm Surge Conditions

As the effectiveness of marshes in protecting coastlines during extreme events, when water levels are at a maximum and waves are at their highest, is poorly understood, a study done by Möller (2014) assessed wave dissipation under storm surge conditions to show how salt marshes provide effective coastal protection. Möller (2014) found that the presence of marsh vegetation caused considerable wave attenuation, even when the water levels and wave heights are at their highest. After comparing wave reduction with vegetation and without vegetation it was found that up to 60% of wave reduction can be attributed to vegetation (Möller, 2014). The other 40% was found to be caused by the bottom friction.

During these experiments salt marsh surfaces were able to withstand large wave forces without a substantial increase in erosion. Salt marshes are thus a reliable part of coastal defense schemes as long as wave height and water depths are considered alongside wave dissipation requirements and ecological conditions necessary for healthy vegetation (Möller, 2014).

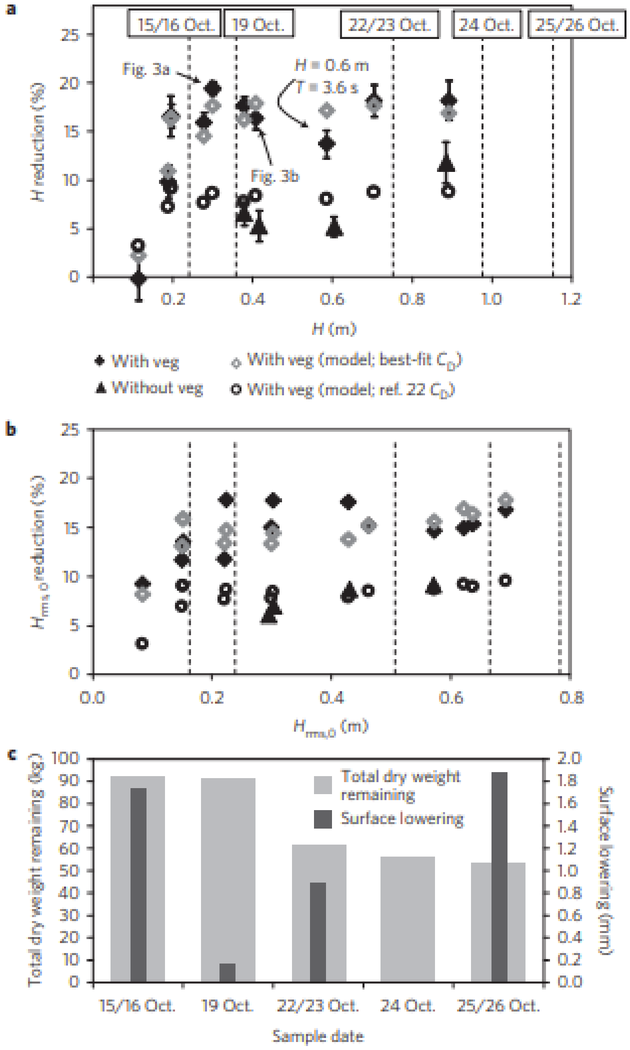


Figure 2.1: Wave dissipation across 40m of vegetated and mowed salt marsh

(Adapted from Möller, 2014)

2.3 Natural versus Gray Infrastructure: Nature’s Solution to Infrastructure Demands

Both natural and gray infrastructure are essential for the success of the economy, society, and environment. Infrastructure around the world enables trade, connects communities, creates opportunities, and protects from the unpredictable natural environment. Without reliable infrastructure, the world would not be what it is today.

In this literature review two different types of infrastructure will be compared: natural infrastructure and gray infrastructure. Gray infrastructure is more commonly known, and refers to, human-engineered structures such as dams, seawalls, roads, pipes, and water treatment plants. Natural infrastructure refers to nature-based systems and is the "strategic use of networks of natural lands, working landscapes, and other open spaces to conserve ecosystem values and functions and provide associated benefits to human populations" (Allen, 2012). Examples of this form of infrastructure include rainwater harvesting, forests, floodplains, constructed wetlands, salt marshes, and green roofs that provide additional benefits for human well-being, such as flood protection and climate regulation (The Nature Conservancy, 2020).

As research grows, natural infrastructure is beginning to be recognized as the smarter asset investment for municipalities. The benefits of natural infrastructure are not only environmental but economic and social as well. Natural infrastructure is also proving to be the better financial investment due to its appreciation in value over time (The Nature Conservancy, 2020). While gray infrastructure, like water treatment facilities and sea walls, depreciate over time, nature-based solutions improve as they mature. An analysis done by New York City concluded that green roofs and bioswales would help meet the city’s water quality goals, saving more than $1 billion compared to conventional gray infrastructure (Talberth, 2016). Similarly, the City of Philadelphia found that the net present value of natural infrastructure for storm-water control ranged from $1.94

to $4.45 million, while gray infrastructure benefits only ranged from $0.06 to $0.14 over a 40-year timeline (Talberth, 2016). North Carolina also did a study comparing wetlands to minimize storm-water runoff and determined it would cost $0.47 per thousand gallons treated, while the gray solution cost about $3.25 per thousand gallons (Talberth, 2016).

While the financial and environmental evidence may strongly lean in the favor of natural infrastructure, there is still a lot of unknowns. There are years of research supporting the efficacy of gray infrastructure that makes communities more comfortable with this infrastructure option. Not only are governments more comfortable, but there are also already developed codes and monitoring plans in place for this more familiar infrastructure. Natural infrastructure also requires careful planning, implementation, and maintenance to be effective (Brown, 2012).

2.4 Approaches to Monitoring Salt Marshes

There are many different approaches to monitoring natural infrastructure such as salt marshes. Governments could utilize remote sensing monitoring or on-the-ground monitoring. On-the-ground monitoring addresses the salt marsh processes (accretion, erosion, subsidence, salt balance, etc.) in person (Tiner, 2006). While utilizing in person monitoring you can analyze vegetation, soil changes, and evaluate wildlife habitat. In the field, samples of vegetation and soils should be collected to confirm visual assumptions and desktop analysis. These samples can also determine carbon content and marsh health. However, on-the-ground monitoring is often too expensive to be maintained regularly over long periods of time (Tiner, 2006).

Desktop analysis and remote sensing monitoring have proven to be effective methods for monitoring salt marshes over time. For example, the U.S. Fish and Wildlife Service utilized aerial imagery to track changes in wetlands in Canfield Cove, Connecticut for the Connecticut

Department of Environmental Protection (DEP). For large geographic areas, statistical sampling analyzing changes in 4-square mile plots is utilized, and area-based analysis, analyzing a complete area for changes over time, is applied for small areas. The Long Island Studies (LIS) Program of the Connecticut Department of Environmental Protection (DEP) provided digital images of aerial photography for Canfield Island Cove and other study areas in 1974, 1981, 1986, 1990, 1995, 2000, and 2004. Six study areas, including Canfield Island Cove, were located along the western shore of Long Island Sound in southwestern Connecticut.

Utilizing the aerial imagers, all study areas experienced a decline in low and high marsh from 1974 to 2004 and a gain in tidal flat (Tiner. 2006). For each study site, the aerial photography was interpreted on-screen, and low marsh, high marsh and tidal flat was delineated and recorded based on the edge of vegetation. Canfield Island Cove specifically experienced a 26% gain in tidal flat, while losing 27% of its low marsh and 4% of its high marsh. Aquatic beds were also reported to appear to decline by nearly 40% (Tiner, 2006). Aerial photos to illustrate these changes for 1974 and 2000 are provided in *Figure 2.2* and *Figure 2.3.*

Figure 2.2: Canfield Island Cove, Connecticut in 1974 (Tiner, 2006)

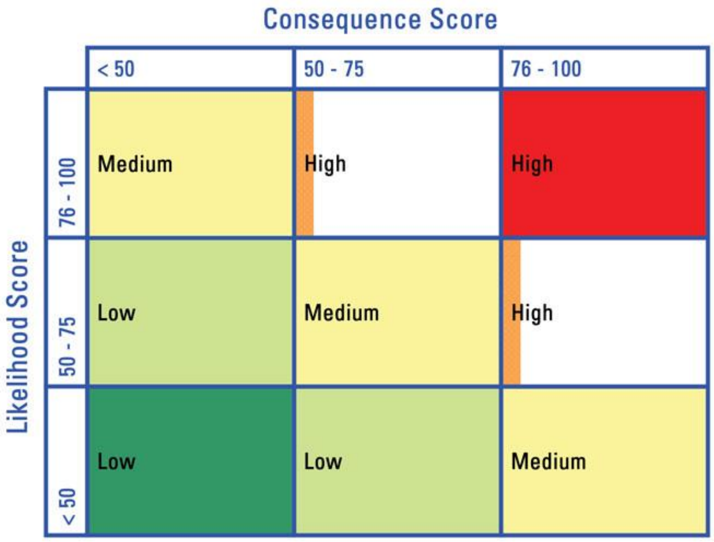
Figure 2.3: Canfield Island Cove, Connecticut in 2004 (Tiner, 2006)

2.5 Developing an Asset Management Plan

An asset management plan defines the activities that will be implemented and the resources that will be applied to meet the asset management objectives and consequently the organizational objectives (Life Cycle Engineering, n.d.). To develop an asset management plan, many factors need to be considered. One of the key aspects of asset management planning is to match the level of service that assets provide to customer expectations. Levels of service include cost, efficiency, quality, reliability, and safety. Future demand and continuous improvement should also be sections of a proposed asset management plan, summarizing the current and future asset management practices including details on the planning and monitoring of the asset. It is also important to include how the assets will be managed and operated at the agreed-upon service level, while optimizing total cost of ownership at an appropriate level of risk. The ISO 55000 Asset Management Standard breaks down several key principles of asset management if companies choose to pursue certification (ISO, 2019).

2.6 Condition Assessment: The Cornerstone of Asset Management

As the nation’s infrastructure matures with time, failures, expensive emergency repairs, and negative public opinions occur more frequently. Due to this increasing issue, utilities are in need of cost-effective condition assessments to easily place their assets in order based on rehabilitation needs and urgency so that limited resources can be properly allocated (Habibian, 2018). The most popular asset prioritization method in recent years has been the risk-based approach. This approach identifies what assets have the highest risk and targets those assets for inspections or interventions (repair, new construction). To quantify what is high risk, three broad categories may be used: physical parameters (age, size, material), conditional parameters (condition), and performance parameters (performance history, maintenance) (Habibian, 2018). Once the probability of failure and severity of consequences is determined, a risk matrix *(Figure 2.4)* is created and is used to determine what assets have the highest priority and the immediate need for inspections and maintenance.



Consequence Score

Likelihood Score	< 50	50 - 75	76 - 100
76 - 100	Medium	High	High
50 - 75	Low	Medium	High
< 50	Low	Low	Medium

Figure 2.4: Risk Matrix for Asset Prioritization (Habibian, 2018)

2.7 Municipal Natural Assets Initiative

The Municipal Natural Assets Initiative (MNAI) has a goal to change the way municipalities deliver everyday services, increasing the quality and resilience of infrastructure at lower costs and reduced risk. The MNAI team works to provide scientific, economic, and municipal expertise to support and guide local governments (Municipal Natural Assets Initiative, n.d.). Specifically, this team guides governments in identifying, valuing, and accounting for natural assets in municipal asset management programs. The goal being to develop and maintain sustainable and climate resilient infrastructure assets (Municipal Natural Assets Initiative, n.d.).

2.8 Ecology and Geo-morphology of Salt Marshes in Georgia

The Georgia coast has approximately one-half million acres of marshland, each ranging from 4 to 8 miles wide. In the US, Georgia has the second largest coverage of marshes, making up about one-third of all salt marshes on the east coast (Salt Marsh Ecology, n.d.). Marshes are divided into five ecological zones based on depth of the tides: levee marsh, low marsh, high marsh, marsh border, and the transitional zone (Marine Extension and Georgia Sea Grant, 2018). The marsh salinity and chemistry are a harsh environment for wildlife, so only certain hardy species are able to survive.

In the creek bank, the lowest elevation of the salt marsh, *Spartina alternifora*, or smooth cordgrass, grows from three to seven feet tall and covers about 90% of the marshes (*Figure 2.5*; Marine Extension and Georgia Sea Grant, 2018). *Spartina* typically does better in a fresh water environment but has adapted to survive in salt water. Other marsh vegetation includes *Salicornia* and *Juncus*. Along with cordgrass, plankton, clams, oysters, shrimp, and fish flourish. Salt marshes also provide important nursery habitats for many commercially important fish species such as blue crab, stone crab red drum, spotted sea trout, flounder, and black sea bass (DNR, n.d.)

Figure 2.5: Modern Marsh hosts tidal creek and mud flat flora and fauna

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Assessment of Gray Infrastructure

Prior to determining an asset management and rating method for salt marshes, it is important to understand the current methods in which gray infrastructure is rated. To do this, data was collected from the 2014-2020 New York Bulkhead Inspection Reports (Geeley and Hansen, 2014) and the 2019 Seawall Condition and Resiliency Assessment for the Town of Bay Harbor Islands (Cummins Cederberg, Inc., 2019). These reports examined the conditions of bulkheads in the New York City Marine Transfer Stations and seawalls in Bay Harbor Island, Florida rating them on the ASCE Routine Condition Assessment scale *(Figure 3.1)*. The ratings “Critical”, given to very advanced deteriorating structures, and “Good”, given to structures with no problems or only minor problems, are rare to come across.

The Seawall Condition and Resiliency Assessment Report for the Town of Bay Harbor Islands explained that sea walls in “Fair” condition will likely need to be replaced in 5-10 years even though it may have 10-15 years of life remaining, while any new sea wall constructed within the next 5 years, between 2019 and 2024, will likely remain until 2050 to 2060 (Cummins Cederberg, Inc., 2019). Seawalls being repaired within the next few years will likely need replacement around 2035 (Cummins Cederberg, Inc., 2019). It is important to consider that the sea walls in this report range from six different types; anchored king pile, battered king pile, battered king/T-pile, battered steek sheet pile, anchored T-pile, and battered T-pile. The type of seawall can impact its life expectancy and performance. For example, the T-pile walls supported by newer batter piles are expected to have a remaining service life of 15 years (Cummins Cederberg, Inc., 2019). These evaluations also considered sea level rise and tidal projections when determining future steps.

Condition Assessment Rating Examples

#	PROJECT	GRADE	COMMENTS	RECOMMENDATIONS	SOURCE
1	Southwest Bulkhead	Good (6)	No structural defects were observed. No indication that structural capacity has diminished from original design.	No repairs or restrictions are recommended at the time. Follow-up inspection in 5 years.	Southwest Brooklyn Converted Marine Transfer Station Bulkhead Investigation Report (2014)
2	9730 W Broadview Dr - Seawall	Satisfactory (5)	Minor cracking along the wet face of cap and mild erosion and necking at piles and concrete wall panels.	A follow-up inspection should be scheduled within 5 years. Minor repairs can be made.	Seawall Condition and Resiliency Assessment for the Town of Bay Harbor Islands (2019)
3	North Bulkhead	Fair (4)	Moderate to heavy corrosion and coaling failure located within the splash and tidal /one of the steel sheet piles and steel anchor tie-backs.	Clean and recoat with pursuant and install a bulk anode cathodic protection system. Inspect again once these are complete and again in 5 years.	Southwest Brooklyn Converted Marine Transfer Station Bulkhead Investigation Report (2014)
4	9930 W Broadview Dr - Seawall	Poor (3)	Concrete erosion in splash zone, cracking at soffit on cap, and corrosion at T-pile anchor heads	Make residents aware of seawall condition. Section must be rehabilitated and repaired.	Seawall Condition and Resiliency Assessment for the Town of Bay Harbor Islands (2019)
5	9601 E Broadview Dr - Seawall	Serious (2)	Moderate cracking at wet face, poor vibration during concrete installation, wall panels have rotation of wall, severe cracking through panels, upland depressions at cracking locations, and T-piles have cracking at spot locations	Make residents aware of seawall condition. Repairs need to be made with high urgency.	Seawall Condition and Resiliency Assessment for the Town of Bay Harbor Islands (2019)
6	9201 E Bay Harbor Dr - Seawall	Critical (1)	Moderate concrete erosion and cracking, critical cracking with concrete erosion and rotation of wall, and critical fractures and flexural failure of king piles.	Make residents aware of seawall condition. Replace or repair as soon as possible with the highest urgency.	Seawall Condition and Resiliency Assessment for the Town of Bay Harbor Islands (2019)

Table 3.1: Rating Examples of Gray Infrastructure from Greeley and Hansen LLC (2014) and Cummins Cederberg, Inc. (2019)

3.2 Wave Reduction Characterization

Surface waves are one of the primary contributors to both salt marsh erosion and sea wall deterioration. Therefore, I focused my assessment of salt marshes on wave reduction to create the monitoring baseline. To estimate the wave reduction capabilities of salt marshes, I derived an equation to account for uncertainty and natural variability to estimate the wave reduction per unit length across a salt marsh.

Utilizing the data collected in Möller (2006) paper for the relationship between relative wave height (H_s/h) and wave height attenuation (%H_s reduction) over three transects in September and December on a salt marsh in the UK, I developed an equation to directly estimate wave attenuation (*Figure 3.1*). To improve fit estimate, data were bin-averaged over varying levels of relative wave height defined as the significant wave height (H_s) divided by the water depth (H_s/h; data given in *Table 3.2* below).

H_s/h	Wave attenuation (% per m)
0.025	0
0.075	0.58
0.125	0.81
0.175	1.14
0.225	1.07
0.275	1.38
0.325	1.75
0.375	1.90
0.425	2.55
0.475	1.96
0.525	1.79
0.575	1.74
0.625	2.14
0.675	2.01

Table 3.2: Bin-averaged values of wave attenuation from Moller (2006).

The bin averages were fit with a non-linear least squares model using a power-law equation. The best fit result for wave reduction per unit length was

$$H_{red/L}(\%) = A(H_s/h)^B \qquad (1)$$

where A = 2.822 and B = 0.5457. Equation (1) suggests that wave reduction scales as approximately a square-root function of relative water depth. Utilizing this equation to derive a total percent reduction in wave height yields

$$H_{red}(\%) = (2.822 * hsH^{0.55})L \qquad (2)$$

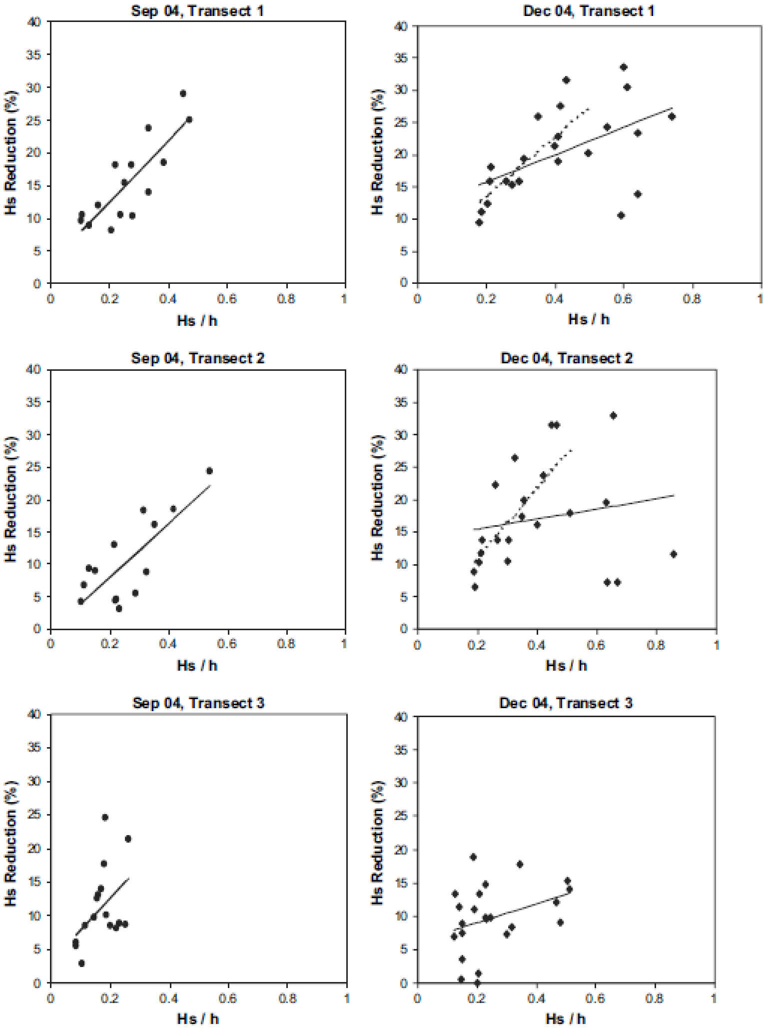

Sep 04, Transect 1
Dec 04, Transect 1
Sep 04, Transect 2
Dec 04, Transect 2
Sep 04, Transect 3
Dec 04, Transect 3

Figure 3.1: Example of data extracted from Moller (2006) for wave attenuation (Hs Reduction) over relative wave height (H_s/h).

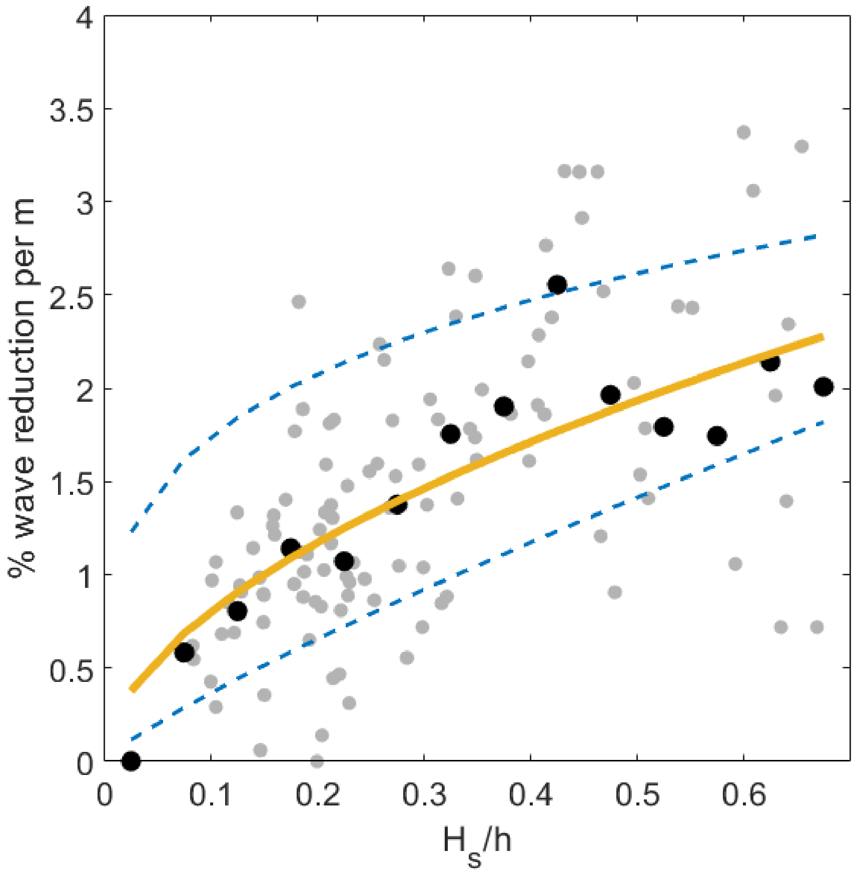


Figure 3.2. Best fit (equation 1) to bin averaged data from Moller (2006). Grey dots are raw data, black dots indicate bin averages, yellow line is the best fit, and dashed blue lines indicate 95% confidence intervals of fit.

I used equation (1) to estimate the wave reduction potential for a wide range of relative wave height and marsh widths *(Figure 3.2)*. To do so, I binned marsh width over 1-1000 m and relative wave height from 0 to 1 at a step of .01. I then calculated the wave reduction potential for each combination to evaluate critical marsh widths *(Figure 3.3)*. The data indicates that critical marsh widths range between 10 -100 m.

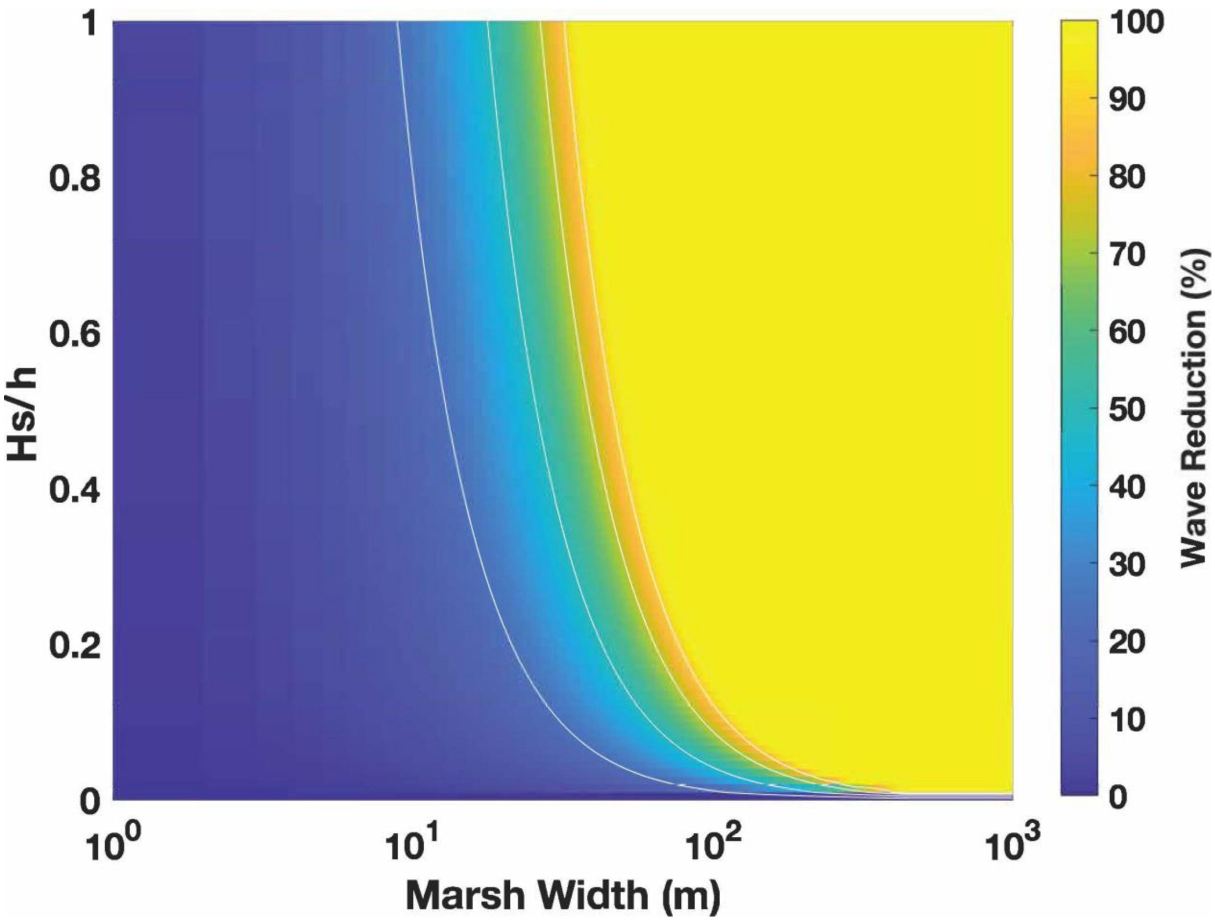


Figure 3.3: Wave reduction capability relative to both marsh width (L) and relative wave height (H_s/h). White lines show 50%, 70%, 80%, and 90% reduction moving from left to right. Marsh width shown on $\log_{10}$ scale.

3.3 Application to Real Data

I then used equation (1) to estimate the wave reduction loss due to erosion and subsidence from existing data sets. To do so, I obtained data from Burns et al (2021) who estimate erosion rates from aerial and satellite photography in 3 distinct salt marshes along the US East Coast in Georgia, Virginia, and Massachusetts. Data was obtained from the Georgia Coastal Ecosystems Long-Term Ecological Research site (https://gce-lter.marsci.uga.edu/public/app/dataset_details.asp?Accession=GIS-GCET-1810). From this data, I extracted the end-point rate of erosion which was estimated as the rate of erosion or expansion (negative values being erosion, and positive values indicating expansion) between the first and last image available divided by the number of years between the images. Horizontal expansion is generally caused by accretion of the marsh and expansion of the vegetation. For each transect, I also extracted the estimated error and the relative skewness of the data by channel order.

I then calculated 1,000 samples of the wave reduction estimates for each location using the coefficients (*A*, *B*) in equation (1) and the associated errors assuming a normal distribution of error around the fit. I also examined a fully uniform distribution with similar results. Next, I used the estimated erosion rate and reported error and skewness to generate 1,000 independent samples of erosion rate for each site. To directly account for skewness, I used a gamma distribution where

$$f(x, k, \theta) = \frac{x^{k-1} e^{-\frac{x}{\theta}}}{\theta^{k} \Gamma(k)} \tag{3}$$

where $\Gamma(a) = (a-1)!$ is defined as the gamma function where *k* and *q* are the shape and scale parameters respectively. In equation (3), *k* and *q* can be related to the mean (m), variance (s^2), and skewness (*S*) of the data as:

$$\mu = k\theta \tag{4}$$

$$\sigma^2 = k\theta^2 \tag{5}$$

$$S = 2 / \sqrt{k} \tag{6}$$

I used the estimated gamma distribution to generate 1,000 random samples of the erosion rate. Since the gamma distribution is absolute positive, to create distributions, I added the minimum value to the observed data to create the distribution, then subtracted the minimum to shift the distribution back to observed values.

I then used the 1,000 estimates of wave reduction capability and the 1,000 estimates of erosion rate to generate 10,000 estimates of wave reduction loss per year as:

$$\frac{H_{red}}{yr} = A\left(\frac{H_s}{h}\right)^B E \qquad (7)$$

where A is the estimated coefficient, and B is the estimated power-law relationship in equation (1) accounting for error.

Once I obtained estimates of wave reduction loss per year, I used the 10,000 estimates to generate a cumulative probability density function (cdf, *Figure 3.4*). Since the data are not normally distributed with relatively large error, using the mean value could represent a 50 or more percent chance of wave reduction losses being higher than estimated. Due to this situation, I used the cdf to evaluate several confidence thresholds (50%, 70%, 80%, and 90%) of which erosion would not be higher than estimated.

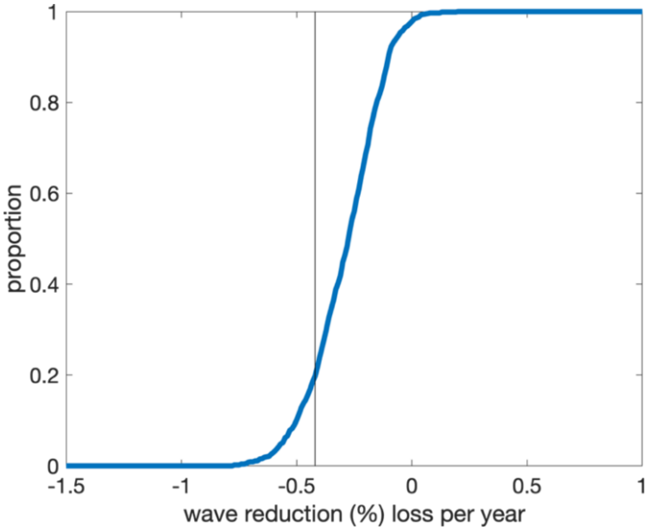


Figure 3.4: Probability density function for wave reduction loss per year for a single transect within the Georgia Coastal LTER. Black line shows the threshold for 80% confidence erosion will not be higher than estimated.

I then used these values to estimate number of years until a specified level of wave reduction loss would occur. To do so, I divided the % loss by a selected level of total wave reduction loss (20%) at the estimated value of erosion at the threshold giving an estimate of how long until this critical wave reduction loss would occur as a measure of infrastructure lifespan. This estimate implicitly incorporated measurement and other error in the system. Finally, I used this time period to estimate how often the transect should be sampled in order to provide good estimates of wave reduction loss through time for effective intervention such as thin layer placement and adaptive management (*Figure 3.5*).

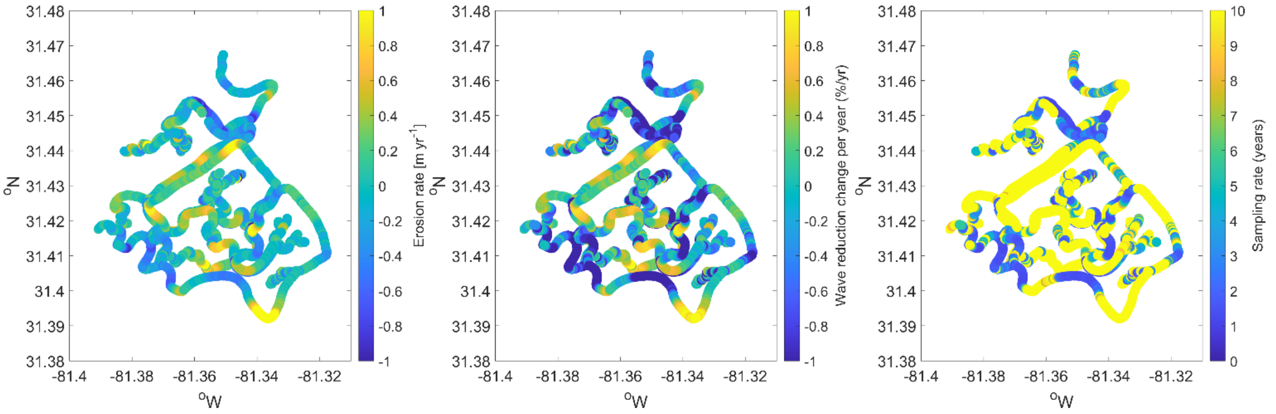


Figure 3.5: Map of Georgia Coastal LTER marsh edges showing erosion rate (left panel), wave reduction loss per year (middle panel), and estimated sampling period to detect change for adaptive responses and interventions (right panel).

3.4 Proposed Routine Condition Assessment Rating for Salt Marshes

Next, I used the estimated time to a threshold wave reduction loss to create an infrastructure assessment grading scale that aligns with metrics for gray infrastructure. I classified areas with wave reduction crossing a defined threshold not met as ‘Critical’, 0-2 years as ‘Serious’, 2-5 years as ‘Poor’, 5-10 year as ‘Fair’, 10-20 years as ‘Satisfactory’, and 20+ years as ‘Good'. These life expectancies were determined by analyzing erosion trends and current life expectancy of salt marshes. These criteria are described in Table 3.3, along with recommendations once the rating is determined. This format is inspired by the condition assessment for sea walls and bulkheads.

This proposed condition assessment rating scale only accounts for wave loss and erosion and does not explicitly include plant health, vegetation, stem density or other salt marsh health monitoring factors. However, these are implicitly included as I have taken data over time from a range of marsh health conditions and used a statistical resampling approach to account for variation in erosion rates and wave attenuation due to vegetation.

A few things should be considered when applying this condition assessment to a salt marsh to accurately determine its rating and subsequent urgency. As a marsh is evaluated on this asset management approach, risk should be at the forefront of the decision-making process. For example, a salt marsh protecting a hospital should be given a higher urgency than a salt marsh with no structure behind it. This also applies to the width of the marsh. When rating a marsh with a larger width, high erosion rate may not be a concern however, a smaller width could be given a critical rating with a that same erosion rate (e.g. a marsh width of less than ~100 m, *Figure 3.3*).

Rating	**Recommendation**	**Life Expectancy**	**Description**
Good	No repairs needed.	20+ years	No visible damage or only minor erosion noted.
Satisfactory	No repairs needed.	10 – 20 years	Limited minor to moderate erosion is observed, but rate is not alarming.
Fair	Repairs are recommended but the priority of these repairs are low.	5 – 10 years	Minor to moderate erosion is observed and the marsh is not very wide, increasing the urgency slightly.
Poor	Repairs should be carried out with moderate urgency.	2 – 5 years	Erosion rate is high and advanced deterioration is observed but the marsh width is still reasonable, and the marsh is not protecting a high priority area.
Serious	Repairs should be carried out with high priority urgency.	0 – 2 years	Erosion rate is high and advanced deterioration is observed. The marsh is not very wide. This could be protecting a high priority area.
Critical	Repairs needed as soon as possible with very high priority and urgency.	Immediate	Marsh is eroding at an alarming rate. A high priority area could be protected by this marsh increasing its urgency.

Table 3.3: Proposed Routine Condition Assessment Rating for Salt Marshes modelled after the ASCE Routine Condition Assessment for Sea Walls and Bulkheads

3.5 Desktop Analysis of Erosion Rate Over Time Utilizing Google Earth

For smaller municipalities and communities, going into the field to determine erosion rate can be a costly and tedious task. Calculating erosion rate utilizing widely available resources, like Google Earth, would be an easier and more cost-efficient method. To test the use of Google Earth as an erosion rate monitoring method, I calculated the erosion rate for 23 transects along the Georgia Coast. The comparable baseline data came from Burns et al (2021) who estimated erosion rates from aerial and satellite photography for the same transects.

Utilizing Google Earth and the historical imagery, I recorded the longitude and latitude of the salt marsh along a transect and a tie down point, such as a house, over time. With those longitude and latitudes, I was able to calculate the erosion rate over that time by using a variation of the Law of Cosines and the number of years the data was collected. While examining the satellite imagery I recorded the marsh line at the edge of the vegetation regardless of high or low tide, to determine the erosion rate. The degree of error in these calculations were also considered.

$$\text{distance}^2 = x^2+y^2-2xy\cos(\theta) \qquad (8)$$

Figure 3.6: Google Earth points for Transect 23 in 2020

Figure 3.7: Google Earth points for Transect 23 in 2010

Transect ID	End Point Rate of Change (EPR) (m/yr)	EPR Error (m/yr)	Google Earth Calculated EPR (m/yr)
23	-0.05	0.08	-0.01
24	-0.2	0.08	-0.12
26	-0.41	0.08	0.93
27	-0.28	0.08	-0.45
28	0.3	0.08	0.22
29	0.15	0.08	0.12
32	-0.01	0.08	-0.34
33	-0.02	0.08	-0.06
401	0.1	0.08	0.28
403	0.07	0.08	0.12
405	-0.06	0.08	0.01
406	-0.12	0.08	0.09
407	0.09	0.08	0.03
408	0.15	0.08	0.03
409	-0.01	0.08	0.19
410	-0.16	0.15	0.19
961	-0.07	0.08	-0.37
962	-0.07	0.08	-0.8
963	-0.04	0.08	-0.70
965	0.01	0.08	-0.31
966	0	0.08	-0.38
967	-0.13	0.08	-0.36
968	-0.22	0.08	-0.18

Table 3.4: Results of Google Earth Erosion Rate calculations compared to Burns (2021) data

Overall, this method of erosion rate monitoring is effective over short periods of time and could be useful when monitoring marshes in good to fair condition. The success of this method is more dependent on the geographic referencing of the Google Earth imagery as well as image quality. With better imagery and georectification, this would be a cost effective and efficient method for monitoring salt marshes and calculated erosion rate. It is also important to note that the

EPR in Table 3.4 is often calculated over periods of 50 years or more, whereas Google Earth estimates were accurate over the past decade. These differences in time period could be a large source of the observed discrepancies. Repeating efforts of Burns et al (2021) over only the past 10-years may improve comparison. If so, this method would be a convenient, cost-effective way to estimate marsh erosion/subsidence.

CHAPTER 4

RESULTS

4.1 Variating Threshold for Acceptable Loss

Using the cumulative probability density function (cdf, *Figure 3.4*), I evaluated several confidence thresholds of which erosion would not be higher than estimated. These thresholds were 90%, 80%, 70% and 50% respectively, where the 50% threshold is roughly equivalent to using the mean value of the data. These different thresholds can be utilized by a municipality to determine their confidence threshold for erosion and the risk they would be willing to take. The 90% threshold offers the most conservative approach while the 50% threshold is a riskier approach but will require less investment in monitoring.

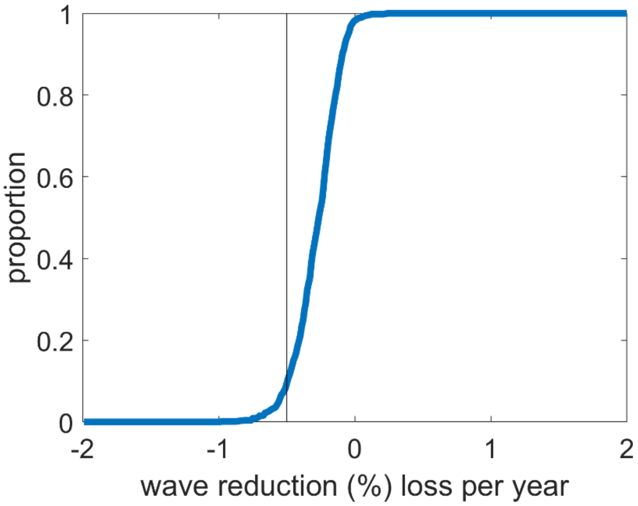


Figure 4.1: 90% Threshold Probability density function for wave reduction loss per year. Black line shows the threshold for 90% confidence erosion will not be higher than estimated.

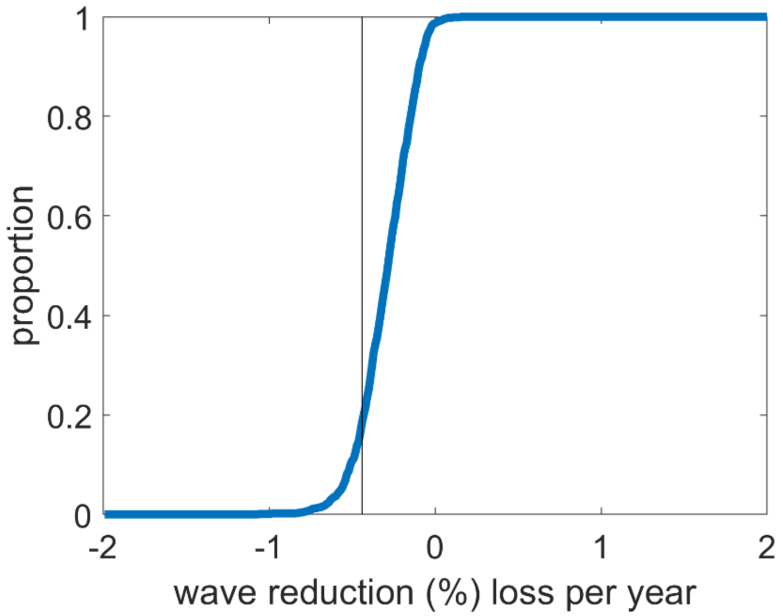


Figure 4.2: 80% Threshold Probability density function for wave reduction loss per year. Black line shows the threshold for 80% confidence erosion will not be higher than estimated.

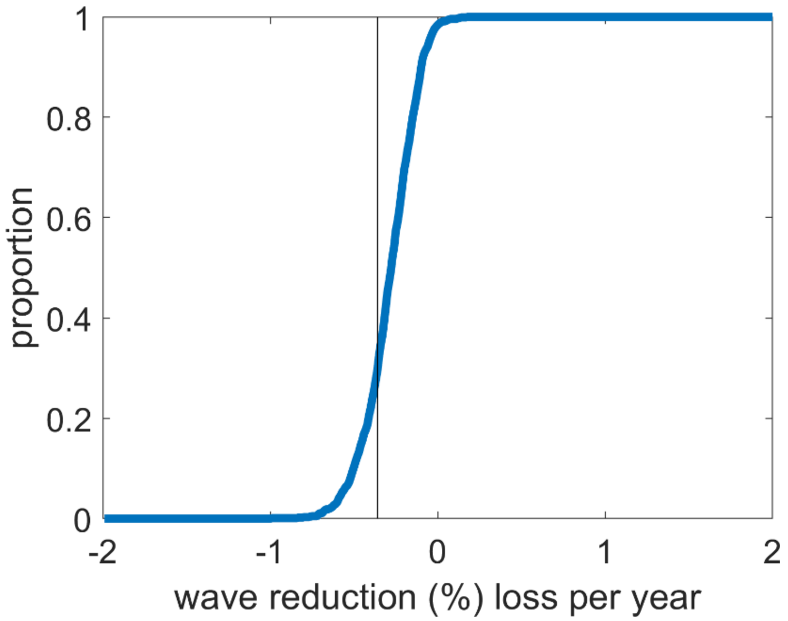


Figure 4.3: 70% Threshold Probability density function for wave reduction loss per year. Black line shows the threshold for 70% confidence erosion will not be higher than estimated.

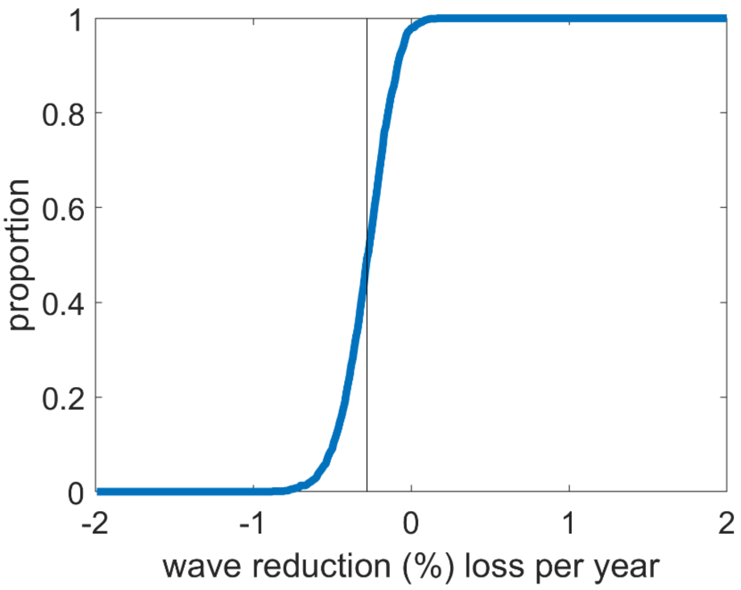


Figure 4.4: 50% Threshold Probability density function for wave reduction loss per year. Black line shows the threshold for 50% confidence erosion will not be higher than estimated.

4.2 Confidence Thresholds: Real World Application

Utilizing these confidence thresholds (90%, 80%, 70%, and 50%) I estimated the number of years until the respective wave reduction loss would occur for a site along the coast of Georgia, along the coast of Virginia, and in Plum Island, Massachusetts. Along the color bar of the figures, bright yellow signifies marsh growth, positive wave reduction and a lower sampling rate required. In all figures this bright yellow color represents a positive and healthy marsh. The dark blue represents areas of concern, including higher erosion, negative wave reduction, and higher sampling rates. Dark blue areas would warrant more monitoring and potentially rehabilitation.

All three sites show significant changes between the 90% and 50% thresholds as expected, especially when looking at wave reduction loss per year and estimated sampling period. For the Georgia Coastal LTER marsh a 50% confidence threshold shows a wave reduction loss closer to 0 for some areas of the marsh, while a 90% confidence threshold is showing wave reduction loss closer to 1 in those same areas (*Figure 4.5*). While seeming small, these wave reduction values could make a large difference when determining risk and rating.

Looking at these results I would recommend at least utilizing an 80% confidence threshold when dealing with marshes protecting important assets and buildings, while a 70% or 50% confidence threshold could be acceptable for marshes playing a smaller role or located away from significant development or infrastructure.

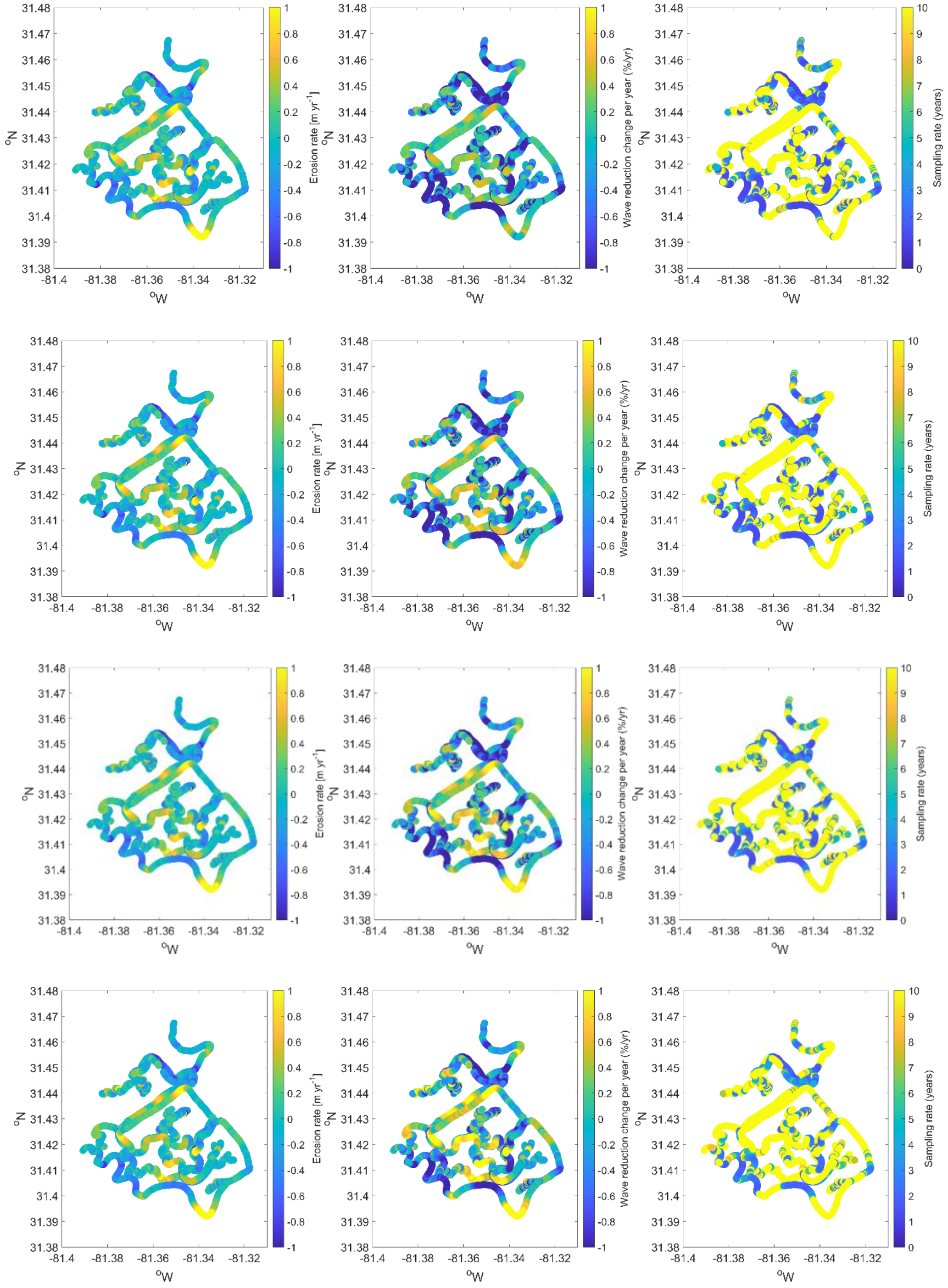


Figure 4.5: Acceptable Loss Maps of Georgia Coastal LTER marsh edges for 50%, 70%, 80%, and 90% confidence (top, middle, and bottom rows respectively) showing erosion rate (left column), wave reduction loss per year (middle column), and estimated sampling period to detect change for adaptive responses and interventions (right column).

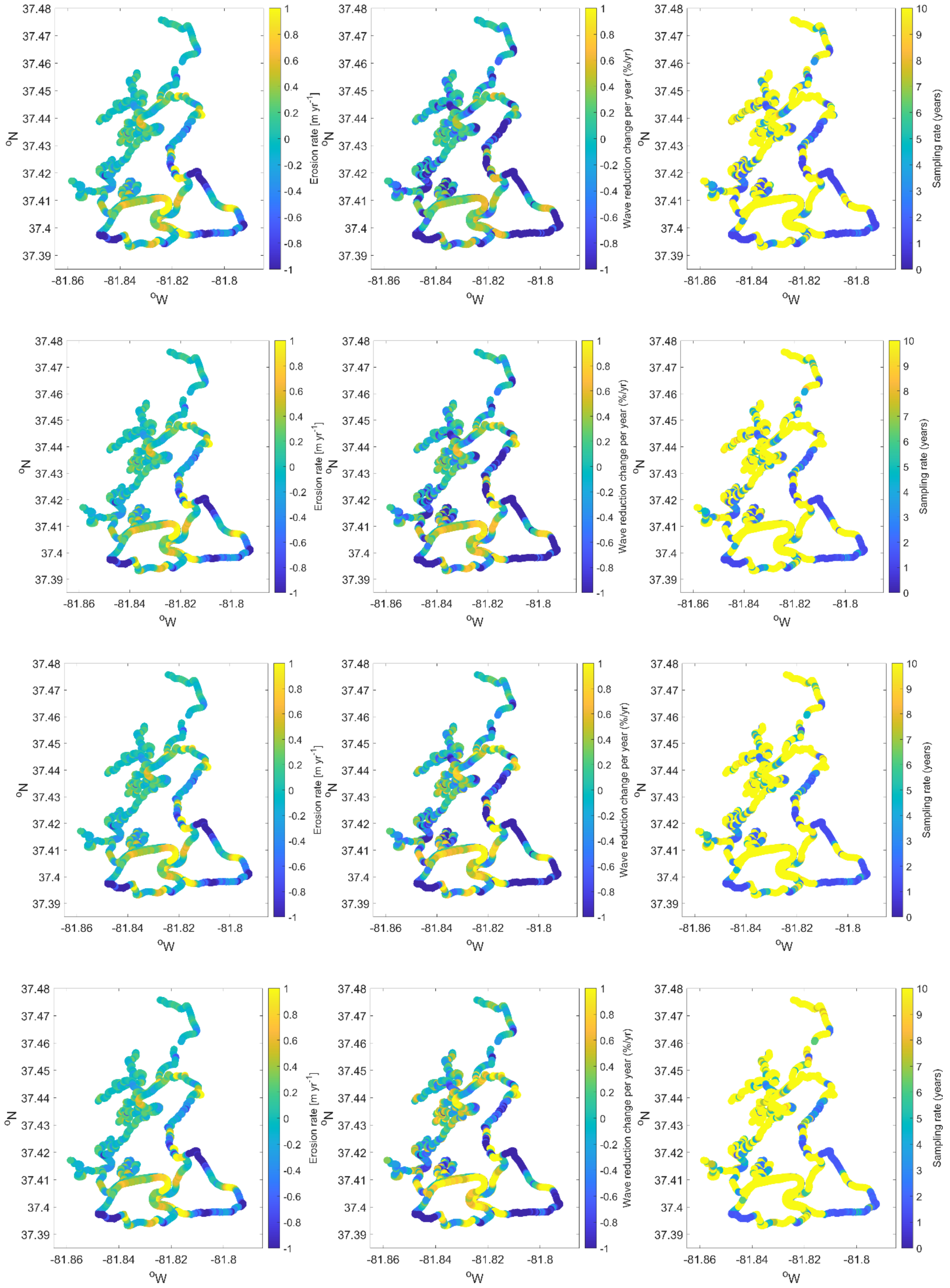


Figure 4.6: Acceptable Loss Map of Virginia Coastal LTER marsh edges for 50%, 70%, 80%, and 90% confidence (top, middle, and bottom rows respectively) showing erosion rate (left column), wave reduction loss per year (middle column), and estimated sampling period to detect change for adaptive responses and interventions (right column).

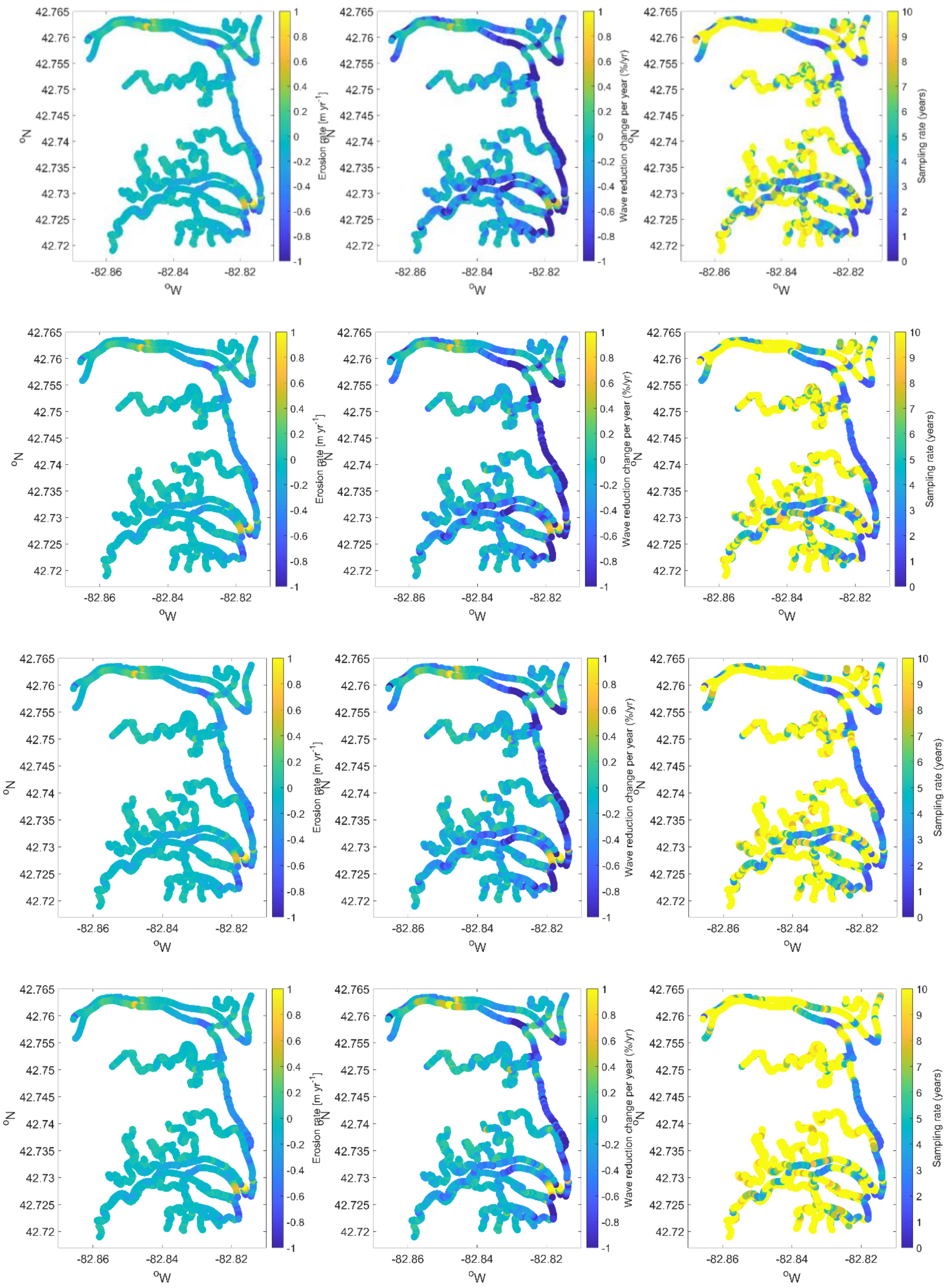


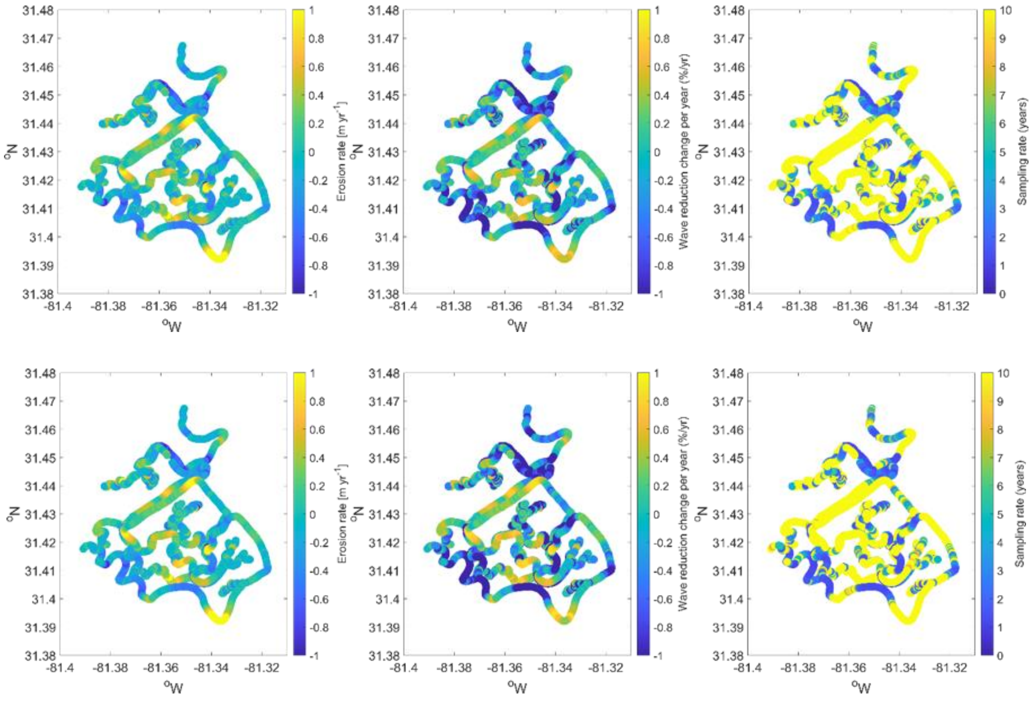
Figure 4.7: Acceptable Loss Map of Massachusetts Coastal LTER marsh edges for 50%, 70%, 80%, and 90% confidence (top, middle, and bottom rows respectively) showing erosion rate (left column), wave reduction loss per year (middle column), and estimated sampling period to detect change for adaptive responses and interventions (right column).

4.3 Variating Relative Wave Height (Hs/h)

When varying relative wave height (Hs/h) from 0.5, 0.8, 1.0 and 1.2 there is minimal effect to erosion rate, wave reduction loss per year, and the estimated sampling period to detect change for adaptive responses and interventions. This is to be expected as the $H_{red/L}(\%)$ equation (9) is weakly dependent on Hs/h. Relative wave height in this equation is raised to the 0.55 power, causing the threshold values to range from 0.7 – 1.1. Thus, Hs/h has a small effect on the results and cannot be seen when tested in the Georgia Coastal marsh *(Figure 4.8).*

$$H_{red/L}(\%) = 2.822(H_s/h)^{0.5457} \qquad (9)$$

In the figures, bright yellow signifies marsh growth, positive wave reduction and lower sampling rates required, whereas blue represents areas of concern, including higher erosion, negative wave reduction, and higher sampling rates. Dark blue areas would warrant more monitoring and potentially rehabilitation. There are minimal changes to the figures when varying *Hs/h*.



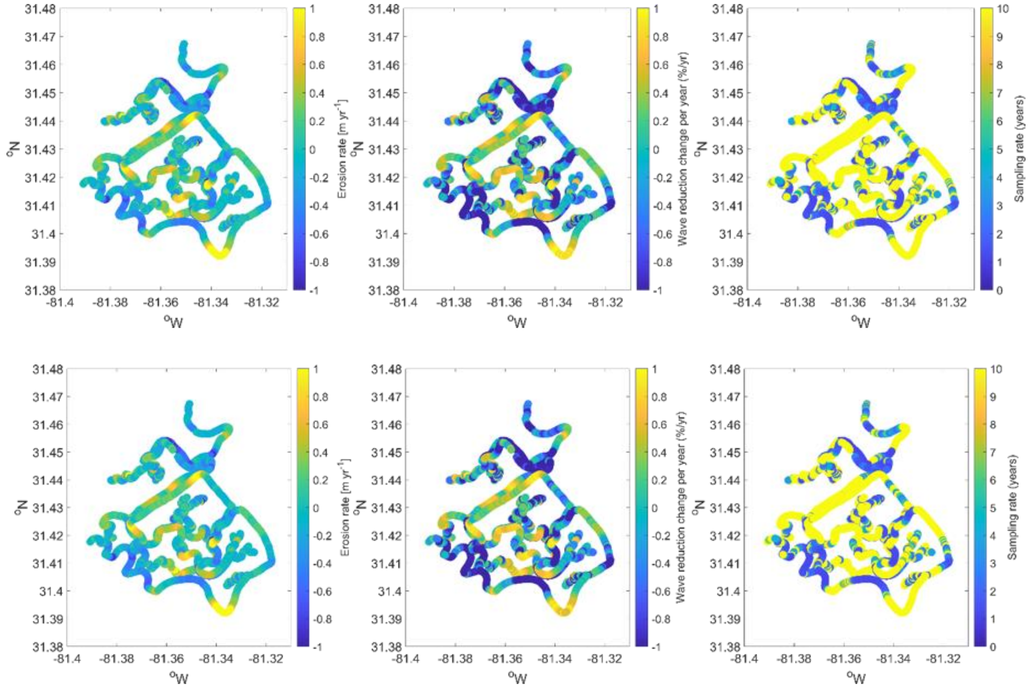


Figure 4.8: Acceptable Loss Maps of Georgia Coastal LTER marsh edges for Hs/h = 0.5, 0.8, 1.0, and 1.2 (top to bottom rows respectively) showing erosion rate (left panel), wave reduction loss per year (middle panel), and estimated sampling period to detect change for adaptive responses and interventions (right panel).

4.4 Sample Number Variations

Finally, I varied the number of samples collected during the infrastructure life expectancy (number of years until a critical wave reduction loss occurs) per year for the Georgia Coastal site to evaluate the risk associated with reduced sample collection. By changing the number of samples desired during the estimated time to a predicted reduction in wave loss capability (estimated life span) to detect change for adaptive responses and interventions, there is a significant difference between collecting 5 samples and 20 samples over the estimated life span. As expected, there is substantially more risk associated with less sampling compared the conservative approach of 20 samples. After analyzing this data, I would recommend doing a minimum of 10 samples over the estimated life span to minimize risk (sampling every other year similar to typical sea wall inspections). If the marsh is protecting a high priority building such as a school, hospital, or government building I suggest increasing these sampling rates. This ensures you are collecting ample information to detect alarming erosion trends or depletion of marsh health.

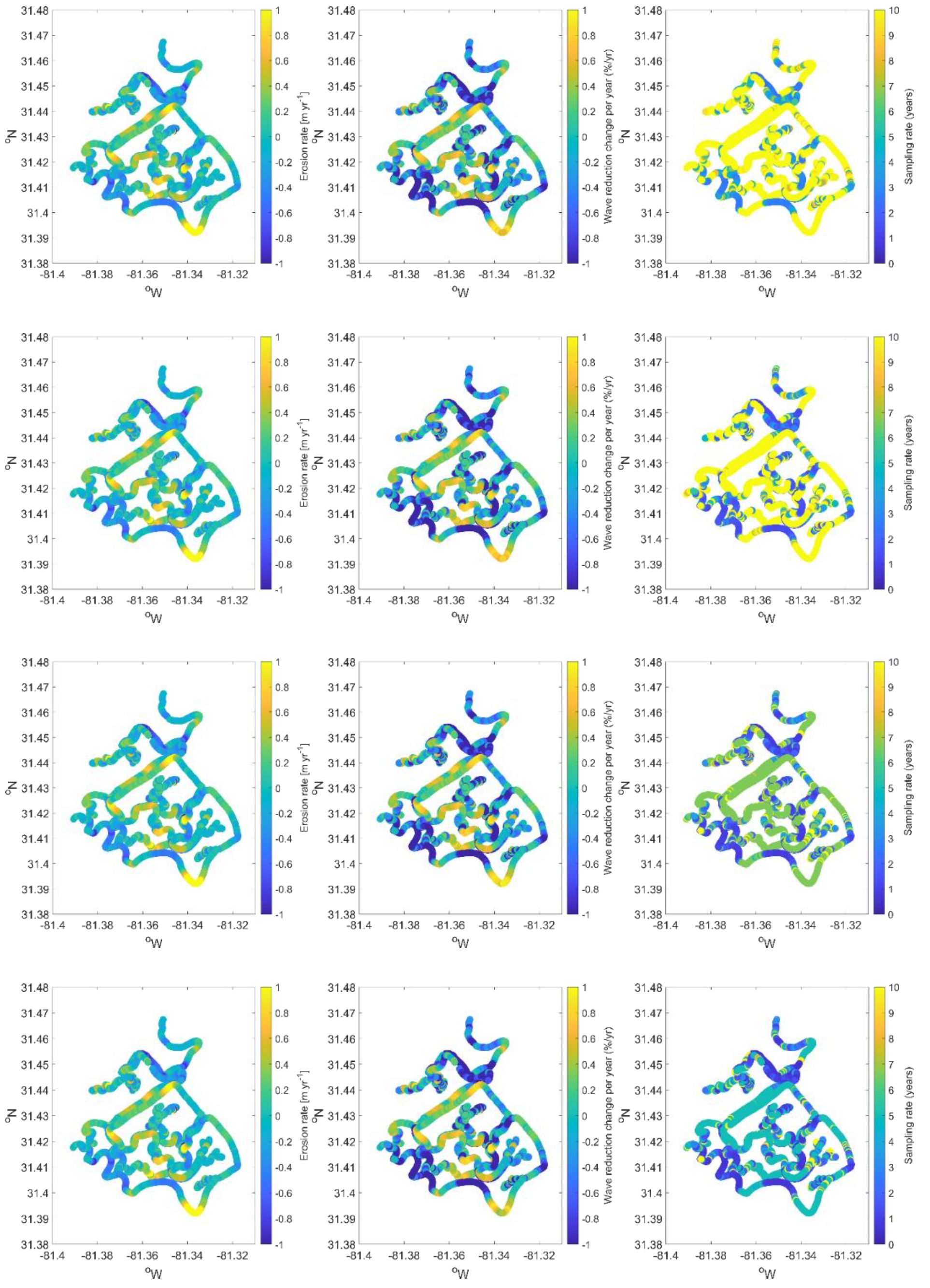


Figure 4.9: Acceptable Loss Maps of Georgia Coastal LTER marsh edges for 5, 10, 15, and 20 samples collected over infrastructure life expectancy (top to bottom respectively) showing erosion rate (left panel), wave reduction loss per year (middle panel), and estimated sampling period to detect change for adaptive responses and interventions (right panel).

CHAPTER 5

CONCLUSIONS, RECOMMENDATIONS, AND FUTURE WORK

Preliminary review of existing natural infrastructure monitoring literature showed that there is no current salt marsh monitoring method as a component of natural infrastructure, and it is not thoroughly researched. Most of the information on monitoring infrastructure focuses on gray infrastructure and the asset management approach the US has utilized for years. Natural infrastructure is a dynamic approach to infrastructure that is constantly evolving therefore making a condition assessment more complex, but not impossible, hence the inspiration for this research. Through this research, I accomplished three core objectives:

1. Understand the current asset management rating approach for monitoring gray and natural infrastructure.
2. Developed a statistical wave reduction model based on erosion rate and real-world data.
3. Formulated a condition rating assessment for wave reduction potential of salt marshes.

My proposed condition rating assessment scale should be a guideline for salt marsh health but should be open to interpretation based on each specific marsh and the municipality or community needs. Based on the level of risk a stakeholder is willing to take with the marsh will heavily impact the marsh rating and remediation needs. Marsh location, environmental aspects, and business needs will also impact the marsh rating and remediation priorities. Therefore, the asset management approach is imperative to this rating scale. Each marsh should be analyzed and rated as a managed asset while considering risk and life cycle. If this is done, the proposed Salt Marsh Condition Rating Assessment scale will work as intended for large and small municipalities.

5.1 Applying the Condition Rating Assessment for Salt Marshes

Utilizing the data from Burns et al (2021), the proposed condition rating assessment for salt marshes was applied to 3 salt marshes along the US East coast *(Figure 5.1)*. These salt marshes are located in the Long-Term Ecological Research Network (LTER). The first site is in the Georgia Coastal Ecosystems (GCE), the second is in the Virginia Coast Reserve (VCR), and the third is in the Plum Island Ecosystems (PIE). These sites represent distinct ecosystems along the US eastern seaboard and serve as sentinel sites where routine monitoring can identify changes in ecosystem response to natural and human caused changes (Burns et al, 2021). Due to the diversity amongst these sites, they are the perfect example of this universal rating assessment approach.

Each site was rated based on erosion rate and wave reduction, not explicitly including other factors that may impact marsh health such as vegetation. These factors were implicitly applied through the statistical modeling of wave reduction potential. This rating was then color coded and mapped depending on these results. Areas around the site that are in critical condition are represented by a deep blue color and areas in good condition are in a bright yellow color. Those areas that are dark blue, lighter blue, or green are the areas that could utilize more resources, such as monitoring and remediation. These methods of remediation are also included in my recommendations.

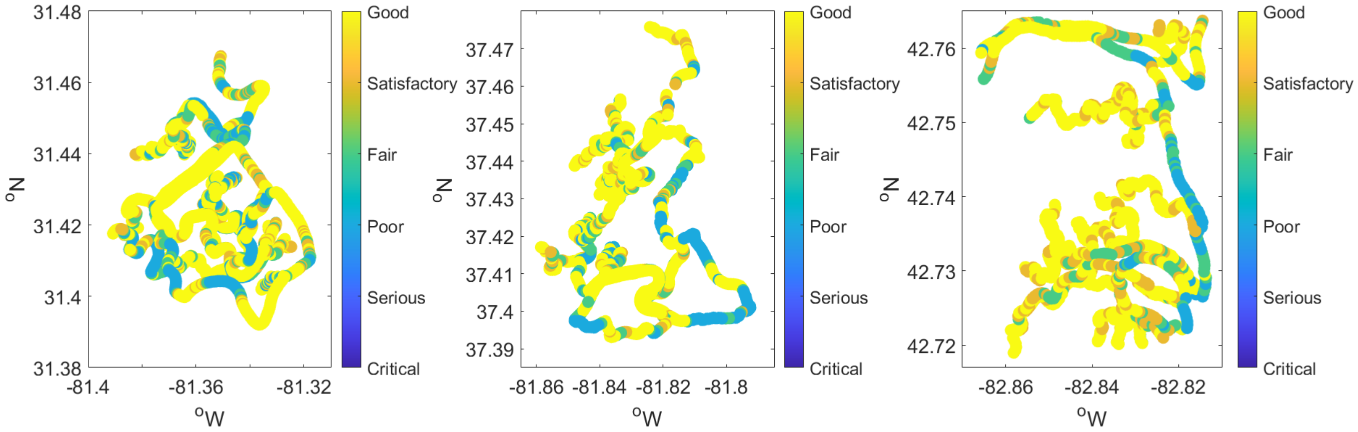


Figure 5.1: Proposed Rating Scale in Real World Application showing Georgia Coast (left panel), Virginia Coast (middle panel), and Plum Island Massachusetts (right panel) rated according to their erosion rates.

5.2 Remediation Recommendations and Interventions

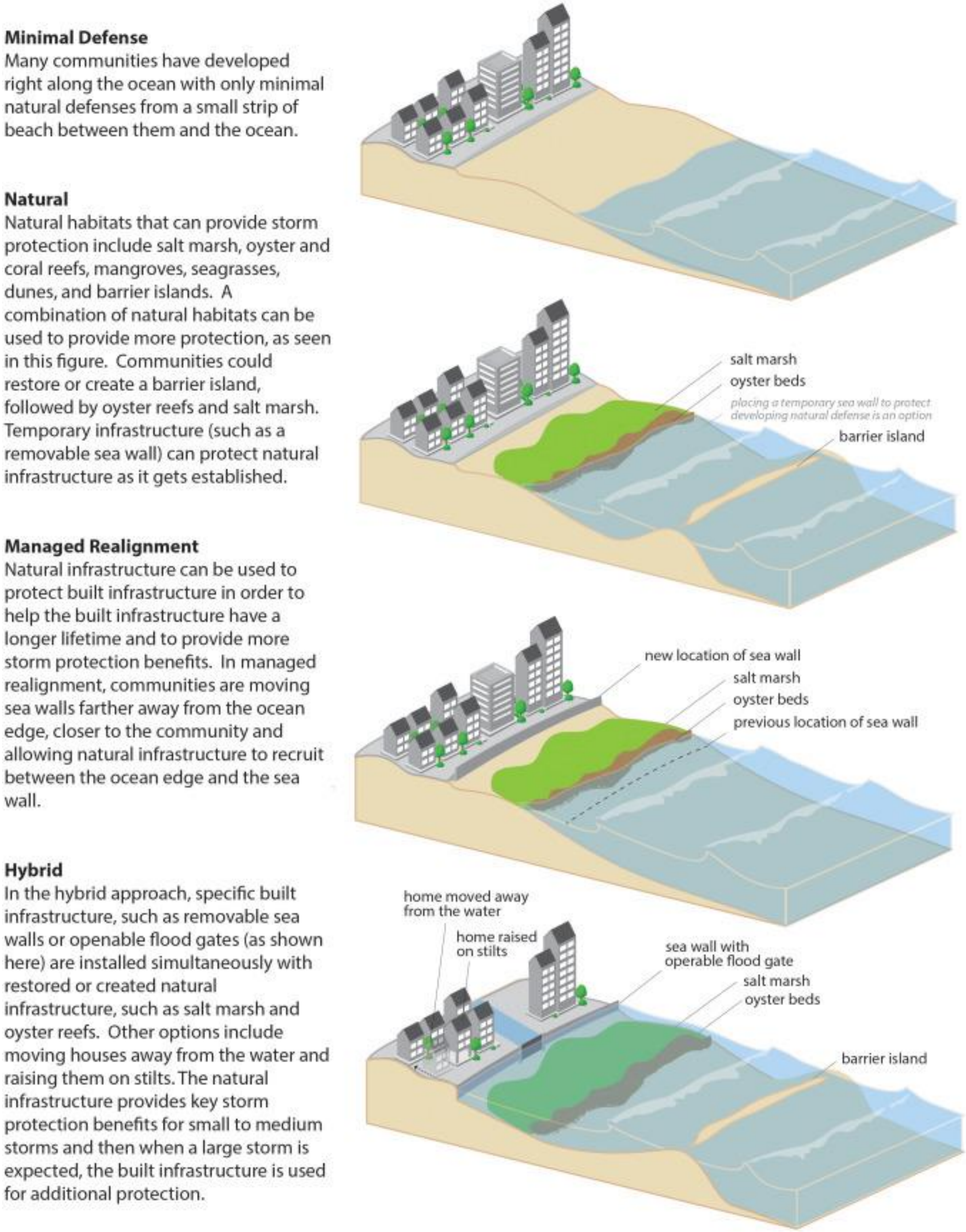
When rating and monitoring salt marshes, marshes rated as critical or serious will need special attention to be restored to healthy conditions. Luckily there are many tested methods to remediate salt marshes that could be utilized. The correct approach will have to be taken depending on the severity and cause of the marsh deterioration.

Dredged material removal can be used to restore marshes that have been impacted by too much fill by reestablishing elevations (Rhode Island Habitat Restoration, n.d.). Thin layer placement is the placement of a thin layer of clean dredged material across the sinking marsh to raise the marsh elevation. This process helps restore and maintain a healthy chemical, physical and biological marsh process by providing stabilization for birds and wildlife to flourish (Holynskyj, 2014). The rating scale I developed could act as a priority siting for thin layer placement interventions. Invasive species may need to be removed to maintain the natural ecological processes and trophic dynamics to allow the marsh to thrive. For example, the removal of

Phragmites has contributed to the maintenance of biodiversity throughout Rhode Island's coastal zone (Rhode Island Habitat Restoration, n.d.). This can also be established by fencing salt marshes to exclude invasive livestock. Fencing is an affordable and low-impact intervention commonly used to protect marshes and has shown striking success (Golden, 2021). Sea walls and living shorelines can also be used in conjunction with salt marshes to allow salt marshes to restore, while still providing coastal protection.

5.3 Hybrid Infrastructure

By providing a condition rating assessment scale for both natural and gray infrastructure, the integration and assessment of hybrid infrastructure can be evaluated in familiar ways. The use of hybrid infrastructure is not only a smart economic decision, but it is also a smart environmental decision. The hybrid infrastructure approach capitalizes on the best characteristics of gray and natural infrastructure. This allows for a greater level of confidence, better adaptability, and allows for innovative designs (Sutton-Grier et al, 2015). Hybrid infrastructure is a clear solution to limited resources and a constantly changing environment.



Minimal Defense
Many communities have developed right along the ocean with only minimal natural defenses from a small strip of beach between them and the ocean.

Natural
Natural habitats that can provide storm protection include salt marsh, oyster and coral reefs, mangroves, seagrasses, dunes, and barrier islands. A combination of natural habitats can be used to provide more protection, as seen in this figure. Communities could restore or create a barrier island, followed by oyster reefs and salt marsh. Temporary infrastructure (such as a removable sea wall) can protect natural infrastructure as it gets established.

Managed Realignment
Natural infrastructure can be used to protect built infrastructure in order to help the built infrastructure have a longer lifetime and to provide more storm protection benefits. In managed realignment, communities are moving sea walls farther away from the ocean edge, closer to the community and allowing natural infrastructure to recruit between the ocean edge and the sea wall.

Hybrid
In the hybrid approach, specific built infrastructure, such as removable sea walls or openable flood gates (as shown here) are installed simultaneously with restored or created natural infrastructure, such as salt marsh and oyster reefs. Other options include moving houses away from the water and raising them on stilts. The natural infrastructure provides key storm protection benefits for small to medium storms and then when a large storm is expected, the built infrastructure is used for additional protection.

Figure 5.2: Examples of coastal defense including natural infrastructure and the hybrid approach (adapted from Sutton-Grier et al, 2015)

5.4 Opportunities for Future Research

This research is just the beginning of a growing framework to provide an infrastructure-based assessment method for monitoring and assessing salt marshes in the US. Salt marshes and other natural infrastructure should be an asset managed and utilized just as often as gray infrastructure and are beginning to be included in the ASCE Infrastructure Report Card. This universal framework will provide easier opportunities to incorporate hybrid infrastructure along shorelines and allocate resources properly. To get to this goal there are a few future studies that should be incorporated:

Moving forward sea level rise and sea level changes should be explicitly incorporated in this research and condition assessment scale. The erosion rates estimated in Burns et al (2021) implicitly incorporated sea level rise as they did not assess whether shoreline change was due to erosion or rising sea levels. I would recommend creating a model to test the impact of sea level rise on erosion rates and marsh health. This would include more of the climate change impact on salt marshes that was not fully encompassed in this thesis. In addition, the flood or inundation capability of salt marshes needs to be estimated using statistical methods similar to those used in thesis or through hydrodynamic modeling so that storm surge protection can also be included in the proposed framework.

I would also recommend testing and applying this rating scale to many other salt marshes, other forms of natural infrastructure, and hybrid infrastructure entities as well. Some adjustments would have to be made to truly encompass all forms of infrastructure but that is the long-term goal where this thesis represents an initial step.

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