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Economic Impact Assessment of Nature-Based Coastal Resilience Solutions in Charleston. Estimating Local Economic Effects With Algorithm-Based Supporting Tool.

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ECONOMIC IMPACT ASSESSMENT
OF NATURE-BASED COASTAL RESILIENCE SOLUTIONS IN CHARLESTON.
ALGORITHM-BASED SUPPORTING TOOL

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ABSTRACT

Coastal cities are at the forefront of the risks induced by climate change. Local communities are adversely affected, but the essential cultural assets and economies are also at risk of damage or destruction. In the efforts to limit hazard risk exposure, local governments are increasingly planning for long-term flood protection. One prospective flood risk mitigation measure is living shorelines or nature-based adaptation. The coastal ecosystems, such as beaches, wetlands, barrier islands, oyster reefs, and salt marshes, deliver multiple benefits to communities, including recreation, natural resources, freshwater, and carbon sequestration. Moreover, when combined with structural solutions, they can effectively reduce water and storm wave energy levels. Despite these positive effects, the implementation of NbS is limited by a scarce understanding of their performance against uncertain sea level rise projections, their economic impacts, and funding gaps.

In this research, I aimed to enforce this knowledge by assessing the economic values of various nature-based coastal adaptation solutions applied to the Charleston Peninsula. Tourism and recreation sectors substantially contribute to the local economy, and my assessment model focuses on them as a potential source of sharing resilience upfront costs. The nature-based adaptation generative algorithm model is spatially explicit and scenario-based, which helps reduce uncertainties. The adaptive interface helps answer my research questions and estimate the performance of Nature-based and Hybrid adaptation strategies in preventing tourism operation disruption over the planning scenarios. The model also evaluates recreational activity induced by proposed green infrastructure to expand the range of ecosystem services incorporated in the methods of economic impact assessment.

DEDICATION

I dedicate this work to people who dream greater than their interests and circumstances. Nothing is impossible with the right intention in the heart, the right thoughts in mind, the right people to support us on our way, and an abiding passion for making this planet a better place to live. As a Russian urban designer and planner, I want to contribute this work to a proactive strive towards brighter and happier cities and against wars, aggression, mismanagement, and misinformation.

This research was conceived long before the dramatic conflict between my home country and the country of a big part of my family and friends began. It was initially focused on protecting the masterpieces of human civilization – historic maritime cities – as the global pandemic has shown our vulnerability to environmental disasters. Here, I must refer to Italo Calvino, whose immortal piece “Invisible Cities” (Le città invisibili) guided my focus on the fundamental values woven into the factual matter of my research. As the plot of this light and the profoundly poetic novel goes, Marco Polo`s storytelling expresses the diverse characters of 55 cities to Kublai Khan as he asks about his empire. In the last chapter, a reader sees them all coming together in the only beloved city of the author – Venice.

As the changes came to our homes in February 2023, I reconsidered the notion of resilience and embraced the broader range of external and internal stresses it addresses. After all, it has a much broader sense and application than solely climate related. With this additional level of dedication, I take my step to make a change and encourage more people to believe in the power of one on our way to a shared, resilient future.

ACKNOWLEDGMENTS

I want to express my gratitude to my extended family, who supported me through my struggle and sleepless nights with this work. I would never have become that perseverant unless my parents and grandparents inspired me with their hard labor in peace and joy. I am thankful to all City and Regional Program staff, especially Dr. Caitlin S. Dyckman, Dr. Eric A. Morris, and Dr Lynn M. Abdouni, for their presence, wisdom, and talent to narrow the topic down when I was falling into the rabbit hole. A great inspiration in optimism, wit, and insight was Dr. John Gaber and Dr. Barry Nocks, the sources of concise advice with a significant impact.

My work with One Architecture and Urbanism in New York in Summer 2022 became the turning point in finalizing my research topic. Their drive and energy in developing better implementable coastal resilience solutions were crucial when I was oscillating between two topics to make a final choice of the idea of this model. Special thanks are dedicated to Matthijs Bouw – the adept of living shorelines and the most bright and optimistic chief I have ever been working with, Travis Bunt for his concise and provisional recommendations, and Justine Shapiro-Kline for her wisdom, modest dedication to collective results, and inspirational elegance in working culture. I appreciate the drive for a global vision nurtured in me by my first academic advisor M.V. Shubenkov who patiently and passionately led my thesis back in Moscow Architectural Institute in 2011. I will be forever grateful to all my Russian and Ukrainian friends and colleagues, who bravely stayed against the criminal actions and were great support during the political conflict. I am particularly grateful to my inspirators, Anna Leksina and Anna Nosova – for the love, talent, wit, and humor - being our only weapons. And finally - to my Muse - for guiding me silently from a distant shore.

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GLOSSARY

Adaptation - adjustment in ecological, social or economic systems aimed to respond to climate change impacts to alleviate adverse impacts of change or take advantage of new opportunities. (Adger et al., 2005)

Attenuation capacities - the ability of natural features, such as wetlands, reefs, or dunes, to reduce the energy and height of waves as they approach the shore, and with that - protect coastal areas from erosion and flooding caused by storm surges and extreme weather events.

Bathymetry - the depth and topography of the seafloor near the shoreline, including the nearshore zone, surf zone, and intertidal zone. Shoreline bathymetry is important for understanding coastal processes such as erosion, sediment transport, and wave propagation, and is measured using sonar, Lidar, and satellite imagery.

Business operation loss - economic losses incurred by businesses due to physical damage and operational disruption caused by a natural disaster. It includes both direct and indirect economic losses.

Chronic inundation - recurrent flooding of coastal areas due to sea level rise happening with the growing frequency even in the absence of a major storm event (UCSUSA, 2017)

Climada (CLIMate ADAptation) - an open-source software tool designed for risk assessment and management of natural hazards. It is a modular system that can simulate and model different types of natural hazards, including floods, tropical cyclones, heatwaves, and wildfires, among others.

Coastal resilience - ability of a coastal system to withstand and recover from disturbances, such as storms, sea level rise, and erosion, while maintaining its essential functions and structure, measured as its capacity to absorb shocks and adapt to changing conditions while minimizing negative impacts on human communities and ecosystems.

Cost-benefit analysis (CBA) - a tool to estimate and compare the costs and monetized value of the expected outputs of an investment or policy actions

Cost-effectiveness analysis - comparative costs and output evaluation.

Co-benefits of ecosystem services - the positive results of actions taken to protect or restore ecosystems and implementing nature-based solutions. Include a wide range of benefits beyond the primary goal of ecosystem restoration, such as improved air and water quality, increased biodiversity, enhanced recreational opportunities, and even economic benefits such as increased tourism or reduced healthcare costs.

Direct benefits - the effects that match with the environmental outcomes of interest.

Discounting - estimating the present value of future benefits and assets.

EBA - Ecosystem-based approaches to adaptation

ECA - Economics of Climate Adaptation framework of risk and cost effectiveness assessment (CCRIF, 2010; ECA, 2009) developed by the Economics of Climate Adaptation Working Group, Global Environment Facility, McKinsey & Company, Swiss Re, the Rockefeller Foundation, ClimateWorks Foundation, the European Commission, and Standard Chartered Bank (Reguero et al., 2014)

Ecosystem restoration - “The process of establishing or reestablishing a habitat that in time can come to closely resemble a natural condition in terms of structure and function.” (Baggett et al., 2014; Schuster & Doerr, TNC, 2015)

Ecosystem services: benefits provided by ecosystems - provisioning, regulating, cultural, and supporting services (Reid et al. 2005).

General/partial equilibrium models - analyze the interactions between markets in an economy assuming they are in equilibrium, or that the rest of the economy is unaffected by changes in that market simultaneously.

Gray infrastructure - engineered or built infrastructure, such as hydropower reservoirs, dams, pipelines, and water and wastewater treatment plants (Gartner et al. 2013).

Gross Domestic Product (GDP) - measure of the total value of goods and services produced within a country's borders in a specific period of time, provides an indication of the size and growth rate of an economy, and is a key indicator of a country's economic performance.

Hybrid infrastructure - conjunction or combination of green and gray infrastructure, such as bioswales, green roofs, constructed wetlands, living shorelines.

Implementation costs - upfront capital and land expenditures associated with a strategy implementation (Verdone, 2015).

Indirect benefits - complementary effects of an intervention benefiting public welfare.

Input-output analysis - economic method that examines the interdependencies between different sectors of an economy. It analyzes how changes in one sector can affect other sectors, by looking at the inputs and outputs of goods and services between sectors.

Internal rate of return – financial metric used to evaluate the profitability of an investment or project (Quinn et al.,2019).

Return on investment ROI – a metric used to measure the profitability of an investment, expressed as a percentage. It compares the gain or loss from an investment relative to its cost, taking into account the time value of money. (BMUB, Emerton, 2017).

Least cost analysis - comparing the costs of alternatives and selecting the option that achieves the outcome at the lowest cost. Often used in environmental and resource management, where limited resources need to be allocated efficiently to achieve the greatest benefits.

NbS - Nature-based solutions that protect and restore ecosystems and adaptively address challenges to provide well-being and biodiversity. (International Union for Conservation of Nature IUCN; Cohen-Shacham et al., 2019; Shiao et al, 2020). These solutions help build resilience through intervention of natural processes into various landscapes (European Commission; Maes & Jacobs, 2015). These actions are supported or copied from nature and aim to bring multiple co-benefits (European Parliament, 2017).

Net Present Value (NPV) - economic evaluation of the costs and benefits of implementing measures considering the initial investment costs and the expected benefits over a certain period of time, adjusted for inflation and discount rate.

RCP - Representative Concentration Pathways (IPCC AR6, WGII, 2022)

Return on investment analysis - financial analysis to estimate the correlation of return on an investment and its cost.

Robustness - capacity to remain unaffected by variations in parameters. Robust NbS achieves the objectives and reduces the risk under uncertain scenarios.

Sensitivity analysis - explores how uncertainty in the model output is attributed to different independent variables.

Time horizon/ planning horizon/ time frame – a period used for the analysis. Must correspond with the lifespan of major infrastructure components as aligns with the decision making terms (Talberth et al. 2013).

Transaction costs - time, labor, and resources to process a deal (Lile et al. 1998).

Uncertainty – scientific or knowledge-gap induced situation when the probability distribution of a result of an action taken is unknown or hardly estimated.

Useful life, or lifespan - timeframe when infrastructure stay productive (WRI, 2019)

Value for money – economic assessment method that involves comparing the costs of a particular project, program, or policy with its expected benefits, and assessing whether the benefits justify the costs. Value for money analysis considers both financial and non-financial costs and benefits, such as social and environmental impacts.

Willingness-To-Pay (WTP) - a method used to evaluate the economic value that individuals place on a particular good, service, or environmental attribute, based on surveying.

INTRODUCTION

Problem

Coastal cities are among the most vulnerable in the face of multiple climatic hazards occurrences and projected events that are expected to hit communities with higher frequencies. The ongoing climate change forces governments to plan for protection considering scientific projections as opposed to the current situation. Coastal ecosystems and communities are the most physically affected by exponentially growing risks induced by climate change. (IPCC, WGII, 2022, UCCRN, 2018). Multiple scientific reports and industry leaders concur with the need for long-term climate preparedness in response to climate change induced hazard risks (IPCC, WGII AR5; Noble et al., 2014; Waggonner & Ball, 2019). These extended horizons raise the question of long-lasting hazard risk adaptation to assure sustained social wellbeing.

Nature based solutions – also called NbS, living shorelines, or ecosystem-based adaptation strategies - bring multiple benefits to communities, economies, and ecosystems, including flood attenuation (Kumar et al., 2021; Moraes et al., 2022; Lebbe et al., 2022; Guerry et al., 2022; Barbier et al., 2011; Shiao et al., 2020; Reguero et al., 2018; Onofri, Nunes, 2020; Mehvar et al., 2018; van der Meulen et al., 2022). Coastal adaptation can be based on "soft engineering" (Baills, Garcin, Bulteau, 2020), or ecosystem-based strategies, such as beach nourishment, wetlands restoration, barrier islands, oyster reefs, and salt marshes (Sutton-Grier, Wowk, Bamford, 2015). Despite their benefits, implementation of NbS is limited by scientific uncertainties and the lack of financing. Also, the effects on the adjacent lands are not easily predictable due to the complexity of the ecosystems and vary on the magnitude and speed of storms. (Sutton-Grier et al., 2015; Langridge et al., 2014). And finally, natural preservation is associated with the conflict of environmental and economic interests, as it competes with the established community uses and economic development (Campbell, 1996, Emerton et al., 2017; Reguero et al., 2014; Baig et al., 2016).

The broader implementation of NbS needs advanced knowledge on their performance, economic impacts, and financing sources. Coastal cities tend to have densely urbanized shorelines due to the traditional role of cultural centers with essential assets concentrated next to the water (Rebuild by Design, 2014; Sutton-Grier et al, 2015; Koch et al., 2009; Gedan et al., 2011; Shephard et al., 2012; Narayan et al., 2017; Barbier et al., 2013; USACE, 2006). The approach to NbS evaluation must involve the full range of benefits, including tourism and recreation, and their dynamics over time along with the expected climate and socioeconomic changes (Sutton-Grier et al., 2015; Kousky, 2014). I aim to contribute to this research gap by answering my research questions and developing an adaptive scenario-based economic model of a protection solution (de Ruig et al., 2019; Graveline & Grémont, 2017).

Research question

I focused on the economic effects of ecosystem-based and hybrid coastal protection in terms of local business activity, to answer the following questions: (1) How do NbS and Hybrid coastal adaptation strategies contribute to the local economy in terms of preventing tourism sector operation disruption and added recreational value in terms of the annual economic activity and? (2) How do these expected effects vary between the time of implementation and their lifespan under the different climate change scenarios? I used an economic development assessment of NbS to estimate their impacts on an urban scale in 10 and 50 years. In this assessment I focused on the response of NbS against two types of flood risks – projected sea level rise and coastal storm surge - as most likely to happen and most damaging events respectively. The economic effects I focused on included revenues of tourism businesses located in the study area - as this sector of the economy has a significant role in coastal areas and especially historic cities. The exposure of tourism and recreation to the two flood risks and the protection provided by the NbS is measured for the two climate change scenarios in the short- and long-term time horizons. Each of the four resulting scenarios considers two levels of water - projected sea level rise and expected extreme storm waves. Thus, “with” and “without project” scenarios set permanent and temporary flood exposures for these hazards. I have found the monetary values of economic impacts for the economic sector of interest to assess the NbS performance.

The case I have chosen for my study is Charleston, SC. The city experiences recurrent floods and as a result has a long history of adaptation proposals. Developed coastal zone, data availability, and the major role of the tourism sector make Charleston Peninsula the proper case for this study (Waggonner & Ball, 2019; Conservation League, 2021; Davis et al., 2021). The studies I used to build my methodology upon comprise the USACE Peninsula study and a number of more ecosystem-friendly alternatives, including One Architecture in consortium with Biohabitats “Imagine the wall” visionary proposal, Coastal Conservation League, and Charleston Civic center (Conservation League, 2021; Davis et al., 2021; Biohabitats, One, Inc, 2021). The barriers to implementing these alternatives are the lack of knowledge and financing sources, which I aim to contribute to with my research.

In planning for coastal resilience, the longer lifespan of a project must be considered to assess its effects during and after implementation. Under the uncertainties on the rates of climate-change induced sea level rise, the proper approach is scenario-based planning, providing several paths of adaptation (IPCC, WGII, 2022; Lopez, 2009; Loayza et al., 2012). I measured economic impacts of ecosystem-based strategies for the recreation and service sectors, following the recent studies and establishing economic metrics of recreation and tourism essential for the lasting community resilience (Vousdoukas, Mentaschi, Hinkel et al., 2020; Reguero et al., 2020; de Ruig, et al, 2019; Herrera, et al. , 2019; Levy, Herst, 2018; Basker & Miranda, 2014). I compared these effects under several climate and socio-economic scenarios contributing to adaptive capacity (Shiao et al., 2020; Reguero et al., 2014; Reguero et al., 2018; Neumann et al, 2010b; Herrera, et al. , 2019; Barbier et al., 2013; Johnston et al., 2002; Shiao et al., 2020; Reguero et al., 2018; Onofri, Nunes, 2020; Baig et al., 2016; Emerton, 2017; Lebbe et al., 2022; Moraes et al., 2022).

Overview

I focused my study on the ecosystem services provided by Nature-based coastal strategies, also called living shorelines, in terms of preventing business interruption and added recreational values. The area of my research is the city center of Charleston, South Carolina. First, I conducted literature review to provide the context and gaps in existing knowledge. I analyzed five major bodies of literature, comprising climate change-induced coastal risks and hazards, coastal resilience approaches, NbS measurements and implementation, the economic impact assessment metrics of these interventions, and finally the status of their implementation in the study area – Charleston Peninsula.

Further, I generated my research method based on literature and state-of-the-art geospatial analysis approaches. My research is framed out as an experimental parametric algorithm. I used GIS and Grasshopper interfaces to connect various factors and four research strands – flood risk, adaptation suitability, economic loss prevention, and recreation co-benefits - to assess the living shorelines performance on the local level. The estimations are geographically explicit and scenario-based so that they can be updated as data availability and the inputs evolve over time and geographic context.

Finally, I discussed the results, policy implications, and limitations of the research and parametric model. I conclude with discussion and explanation of the data gaps and further research, including testing of the model in other comparable localities, expanding component parts, refining the data, and solving the compounding errors. The contribution to the economics of nature-based coastal adaptation is discussed in the conclusion fostering the knowledge on implementation of the Nature-based strategies (Levy, Herst, 2018).

CHAPTER ONE

LITERATURE REVIEW

With this part of my study, I collected the existing knowledge on the following topics: ecosystem-based coastal protection approach in the context of ongoing climate change risks; development and evaluation of resilience approaches; the combination of adaptation and mitigation goals; and the factors of NbS implementation. The literature strands covering economic risks of climate change and economic benefits of addressing them with ecosystem-based solutions are central to developing my research methodology. The simplified structure of the literature review and its linkages to the research method is illustrated in Table 01.

Table 01. Simplified literature review structure

	Literature strand	Content	Method strand	Input	Research gaps
1	**Climate change**	Current state of affairs and Climate projections	01 - Vulnerability assessment	RCPs and local projections	Changing emission patterns
		Coastal hazards	01 - Vulnerability assessment	Coastal hazard types and projections	Ecosystems reaction on changing weather patterns
		Coastal vulnerabilities and risks	01 - Vulnerability assessment	Types of risks for the coastal communities	Environmental risk is hard to evaluate
2	**Coastal resilience**	Resilience concept	Methodology overall	Evaluation perspectives - social, economic, environmental	Complexity to establish comprehensive metrics
		Approaches - recovery, adaptation, mitigation	02 - Adaptation strategy, 03 - Adaptive capacity	Synergy of adaptive capacity and risk mitigation	
		Adaptation and stabilization planning	02 - Adaptation strategy	Methods of coastal protection	Financing, performance under various scenarios
3	**Nature-based stabilization solutions**	Regional applicability	02 - Adaptation strategy	Types of ecosystem- based solutions	
		Evaluation	03 - Adaptive capacity, 04 - Co-benefits, 05 - Scenarios	Values and approaches, parameters of flood attenuation	Lack of the uniform assessment, changing nature
		Implementation	03 - Adaptive capacity, 04 - Co-benefits	Potential impediments, external factors	Long-term maintenance and adaptive capacity
4	**Economic impacts of NbS**	Impact assessment	03 - Adaptive capacity, 05 - Scenarios	Evaluation criteria and methods	
		Economic benefits and co-benefits	04 - Co-benefits, 05 - Scenarios	Recreation and other ecosystem benefits	Lack of established metrics

Part One. Climate change

Context

Climate induced temperature shifts have occurred several times in the last millennia, although we are facing the unprecedented acceleration of these trends currently. They affect both natural and built environments across the world, imposing major risks on the centerpieces of cultural and economic activity – coastal cities. Coastal floods have already displaced over 650 million people across the globe in the last 35 years (Kocornic-Mina et al., 2020), and according to projections, will affect over 800 million coastal citizens with the high magnitude flood events by the year 2050 (UCCRN, 2018). Since 1988, the Intergovernmental Panel on Climate Change plays a leading role in climate change science, impacts, and policy recommendations. Their comprehensive reports inform nations of the status and trends of climate change up to the year 2100. The progress in GHG emissions mitigation has demonstrated only modest results, and the communities still need to adapt to the changing climate to protect cities, ecosystems, and resources for the future generations (UCCRN, 2018; Kopp et al, 2019; IPCC, WGII, 2022; Kirezci et al, 2020).

Climate projections for the coasts

Internationally accepted scenarios of climate change constitute Representative Concentration Pathways (RCPs) and Shared Socio-economic Pathways (SSPs) - climate future projections based on GHG concentration trajectories. The RCPs and SSPs anticipate 2100 warming of 3.3°C to 5.7°C for the highest emission projection SSP5-8.5, of 2.1°C to 3.5°C under the intermediate SSP2-4.5, and of 1.0°C to 1.8°C under the lowest -SSP1-1.9 (IPCC, WGII, 2022). The Paris Agreement set the target of limiting temperature rise to 1.5 C, whereas current state of affair shows that we have surpassed this level. (Clark et al, 2016; C40, UCCRN, 2018;

UNFCCC, 2016). The estimates of sea level rise under those scenarios range from 26 to 178 cm by 2100 causing people and ecosystems to face higher coastal flood risks in upcoming decades (Bamber et al., 2019). Multiple additional studies have been conducted to enhance local projections under a broader array of changing natural conditions, such as ocean currents, topography, storm surge records etc. (Rutgers, 2020; NJDEP, 2020)

The main coastal risks considered in research papers are increasing temperatures and melting glaciers at the poles, that contribute to sea level rise, intensify storm events, salinize aquifers, alter oceanic currents, manifest habitat loss, and Impact health (Clark et al, 2016; Kopp et al 2019; IPCC 6th, WGI, 2021; Cann et al, 2013). RCP8.5, or "Business as usual", scenario implies that by 2100, the ratio of two main coastal risks affecting communities will be 68% of tide and storm events and 32% for the sea level rise. No protection will cause an increased exposure of 48% of the land area, 52% of population, and 46% of the assets. (Kirezci et al, 2020)

Risks caused by changing climate

Physical impacts

Both human communities and ecosystems suffer from erosion, floods, and extreme precipitation altering the geophysics of coastal zones. Among the consequences of these damages are displacement, limited recovery capacity, migration, and fragmentation (IPCC 6th, WGI, 2021; Hsiang, Kopp, 2018). Coastal communities are susceptible to worsening hazards in general (UCCNR, 2018), with 10-13 % of the world population living in Low Elevation zones within 10 m of the sea (McGranahan et al., 2007). Moreover, socially vulnerable groups have considerably lower opportunities to recuperate after disasters, while the numbers of these projected episodic coastal flooding exposure will increase from 128–171 million to 176–287 million in 2100 under RCP8.5 (Kirezci et al, 2020). Beyond the health risks and property damage striking those living next to the ocean, cross-contamination, infrastructural disruption, and community assets disruptions exacerbate the negative effects (Anderson, D. L., Ruggiero, P., Mendez, F. J., Barnard, P. L., Erikson, L. H., O'Neill, A. C., et al., 2021).

Environmental risks

The impacts on ocean life is observed on different scales, including ecosystem degradation, chemical and nutrient pollution, overharvesting of marine fauna, invasive species (IPCC, WGII, 2022). These aspects of climate change are explored by environmental science and supported by environmental groups such as the Nature Conservancy, UN Habitat, Restore America's Estuaries and many others. The research on the loss of habitats is building along with the realization of their value for human communities (Sutton-Grier et al., 2015; Arkema et al., 2013; Smith et al., 2020; Koch et al., 2009). Severe loss of coastal habitats is costly for communities in terms of ecosystem services, such as storm impacts reduction, carbon sequestration, and filtering runoff. Habitat restoration supports economies by providing opportunities for recreation and tourism. (Wharton, 2020).

Fiscal stress

The research reveals extensive financial risks for communities located within the coastal areas, with estimates from the $10s to $100s of billions annually by the end of this century (Neumann et al, 2021). Some papers focus on evaluating the areas projected to be chronically inundated, also involving the direct harm to the economies and ecosystems (UCSUSA, Spanger-Siegfried et al., 2017). Coastal storms cause infrastructure risk and damage that hinder evacuation routes, disrupt energy and water supply, and other vitally important city operations supporting communities and economies. The research evaluates global equivalents of an overall loss in the range from $ 8 billion to $14 billion in the case of no protection (Kirezci et al, 2020).

The risks for coastal properties are approximated as $7.4 B loss in value when compared to the homes located in the areas not exposed to the flood risks (Burgess & Rapoport, 2019).

Part two. Coastal resilience

Perspectives on resilience

The concept of resilience

Resilience is commonly referred to as a system's adaptive capacity and ability to absorb external stress and reorganize to accommodate the change while keeping its identity and function (Holling, 1987, 2001; White,2010; Walker et al., 2004; Raymond et al., 2017). The climate-related definition introduces a city's ability to prepare for the ongoing risks by minimizing social, environmental, and economic loss, and enhancing timely recovery in the aftermath of disasters (Levy, Herst, 2018). Three main characteristics of socio-ecological resilience include maintaining function, self-organization, and capacity to adapt (Oktari et al., 2020).

Social, environmental, and economic vistas in coastal resilience

Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed. Reducing it and boosting its adaptive capacity is an important goal of anticipatory resilience planning (Klein and Tol, 1997; Wiering et al., 2015). The literature notes the need for integrity of resilience dimensions and factors to enhance the performance and achieve a more comprehensive approach sought for the internal ability to withstand a disaster (Mileti 1999, Godschalk 2003, 2007; Lu, Stead, 2013). The social sciences view resilience through the lenses of communities' essential needs, primarily focused on safety and welfare. This perception relegates the ecosystem side of this conflict to the background. The latest progress of the public awareness on the climate change brings the ecosystems into consideration as the major component of the broader array of resilience dimensions (Sutton-Grier et al., 2015;

Narayan et al., 2016; Wyatt et al., 2017). In addition to offering essential protection from hazards, ecosystems play a vital role in sustained natural balance and ecosystem values generation (Barnes and Virget, 2017; Hallegatte et al., 2013; Masselink & Lazarus, 2019; Wyatt et al., 2017). Critical coastal ecosystems are threatened by both hard infrastructure and impacts from a changing climate (Defeo & McLachlan, 2005; Dugan et al., 2011; Guannel et al., 2015; Heady et al., 2018; Wedding et al., 2022).

Coastal economies` resilience is affected by both the hazard threats and mismanagement of development and operation of the coastal areas. As such, research shows that the extensive economic growth creates considerable economic risks in the short term, in addition to the longer-term land loss and other climate-change induced damages (Reguero et al., 2014)

Recovery, adaptation, and mitigation q

Recovery planning policies are focused on the aftermath of a disaster. Having a recovery plan coordinates the actions in case an emergency happens. Such reactive approaches require minimal upfront investment, making it a common practice prior to our social understanding of climate change. Rehabilitation actions involve removal of debris, damage assessment, grant assistance applications, dwellings, utilities, and infrastructure reconstruction priorities, repair and re-occupancy, and temporary housing. (Berke & Campanella 2006; Schwab 2014; Johnson 2014b). The limitation of this approach is the growing probabilities of hazards and respective risks for communities (Alberini, Chiabai, and Muehlenbachs, 2006; Kelly and Adger, 2000; O'Brien, Sygna, and Haugen, 2004; Tol and Yohe, 2007; Yohe, 2000; Yohe and Tol, 2002).

Climate policies for the pre-disaster risks reduction can integrate adaptation and mitigation goals (Swart & Raes, 2007; Di Gregorio et al., 2017). Though the adaptation approach is becoming broadly practicable, it has the limitations of the low accountability for the future climate changes reduction. Adaptation options are limited in capacities to offset climate change impacts on coastal ecosystems, but in the larger scale they can integrate mitigation measures (IPCC, WGII, 2022; Chausson et al., 2020; Baills et al., 2020). Mitigation approach is more strategically oriented on the long-term changes (Rose 2004b, 2007; Godschalk et al., 2009). It progressively reduces GHG emissions and other climate-related risks for the communities. It can involve relocation and retreat if these are the only available measures to enforce sustainable ecosystem and social balance.

Mitigation

Tools and regulation

Land Use Planning is the major mitigation planning tool conducted mainly through strategic comprehensive planning (NRC, 2012; Godschalk, 2003; Berke et al., 2015). Mitigation approach is integrated in resilience plans pursuant to Disaster Mitigation Act , and is performed with the higher-level frameworks (DMA, 2000; IPCC, WGII AR5, Chapter 14.3 Table 14-1, Noble et al., 2014). The array of public funding discussed constitutes the major part in most mitigation measures (Levy & Herst, 2017) including direct grants , CAT funds, budgeting, and FEMA mitigation grants. The growing risk exposure means that the federal support may be insufficient in future years. Multiple researchers highlight the issues related to ample federal post-disaster funding (Burby et al.,1999, Godschalk et al. 1999). Few studies reported synergies or trade-offs between climate impact and GHG mitigation outcomes of ecosystems such as saltmarsh, created wetlands, and tropical and subtropical grasslands (Burden, Garbutt, & Evans, 2019; Ward et al., 2016). Grasslands store over 10% of terrestrial biomass carbon (Follett & Reed, 2010), and could sequester one billion tons of carbon annually (Smith et al., 2020). Moreover, they may be more reliable as carbon sinks than forests in regions facing increased drought and wildfire risk and forest dieback because of increasing climate stress (Dass, Houlton, Wang, & Warlind, 2018; Allen et al., 2010; Chausson et al., 2020)

Adaptation

Sustainable approach considers the synergy of long-lasting economic, social, and environmental goals for communities' welfare. Coastal adaptation planning generally follows four scenarios: protection, accommodation, retreat and no action (Vousdoukas et al., 2020). The factors defining resilience approaches are dictated by the GHG emissions, sequestration, federal and state legislation consequently dependent on the political climate in an area, communities' priorities, and available resources (Tol et al., 2008; Berke et al., 2015; Kreibich et al., 2022). Among the various approaches to protect communities from SLR and coastal hazard risks are structural, social, and institutional approaches incorporating multiple resilience planning tools (Peterson, 2019; Kousky et al., 2021; IPCC, WGII AR5, Chapter 14.3 Table 14-1, Noble et al., 2014). I further focus on the structural approaches to coastal protection as the category includes and provides alternatives to ecosystem-based protection.

Modification of development:

This approach is widespread due to its applicability to the cases of moderate but recurrent climate risks and a community`s will to keep the status quo. These include building codes and retrofits, flood insurance programs, tax incentives, flux zoning, and lower-impact development ordinances are supporting the shift towards less impactful and potentially less affected coastal zone development (Atlantic Coastal Storms Team, 2010; Baills et al., 2019; Kousky et al., 2021). Working with existing housing is a long and challenging process, while the planners must consider the tools for the future resilient development and use the post-disaster opportunities for updated zoning and development incentives (Godschalk et al., 2000).

<u>Retreat</u>

Facilitated re-location, preservation and managed retreat are conducted through conservation and restoration of natural open spaces through buyouts, acquisitions, shoreline setbacks, rolling easements, and other zoning tools (Dyckman et al., 2014). Coastal retreat manifests an array of beneficial community uses and is preferred from an environmental resilience perspective. Floodable grass parks, wetlands, improved views, recreational functions are steering development away from the coast (Powell et al., 2019).

<u>Stabilization:</u>

Stabilization measures involve multiple tools to protect the coastal zone in its status quo preventing land loss and flooding in the short-term (Alberini, Chiabai, and Muehlenbachs, 2006; Kelly and Adger, 2000; O'Brien, Sygna, and Haugen, 2004; Tol and Yohe, 2007; Yohe, 2000; Yohe and Tol, 2002). This is the oldest approach to coastal planning as it evolved from the perception of nature as an adverse external power, using hard infrastructural barriers against the threat. It has evolved with the growing realization of essential balance between anthropogenic and ecosystem structures to provide sustained protection through nature-based solutions. The major rule to choose a proper approach from the Dutch practice is ‘hard when really necessary, soft where possible’ (Meulen et al., 2022). Dutch coastal management has been based on sand nourishment since the 90s, which is practiced to ‘hold the line’ to stop the erosion. (Meulen et al,. 2022). Generally, the European approach moves forward the NbS since 1980s.

Hard infrastructure

Engineered flood retention infrastructure - levees, groins, seawalls, breakwaters and storm surge barriers - were traditionally used before the mid-20th century, before their negative effects became apparent (Cooper et al. 2020; Pilkey et al., 2011; Pranzini and Williams, 2013).

Reliable and predictable on the one hand, they cause negative consequences over time of operation, specifically affecting vulnerable coastal ecosystems and adjacent communities. Hard constructions alter coastal zone configuration, tidal dynamics in the estuaries, marine and coastal habitats, and cause economic loss. (Leuven, Pierik et al, 2019; IPCC, 2022; FEMA, P-55, 2011; Gittman et al. 2016, Dethier et al. 2017, Powell et al. 2019; NRC 2007, Defeo et al. 2009).

Soft infrastructure

Soft, or nature-based infrastructure, is distinguished from the natural landscapes in that it is built and maintained to provide the coastal flood protection while recreating local ecosystems (The International Institute for Sustainable Development, FEMA, 2019; Sutton-Grier et al., 2018). It both addresses the external challenges to the benefits for community welfare and ecosystem dynamics and biodiversity while being resilient in the face of climate change (Seddon et al., 2021; Seddon et al., 2020; Gillespie et al., 2014; Wedding et al., 2022).

Adaptation solutions with both hard and soft components - hybrid infrastructure – combine benefits of coastal habitats and system protection, as well as the adaptation to extreme storm events (Gittman et al. 2016, Dethier et al. 2017, Powell et al. 2019; Meulen et al., 2022). The U.S. Army Corps of Engineers introduced the Engineering with Nature Initiative (USACE, 2019) to create multi-functional infrastructure for a broader range of economic, environmental, and social benefits. (FEMA, 2019). Even though NbS have multiple community and ecosystem benefits, a significant barrier to implementing the green versus gray infrastructure is its low predictability of the level of service under specific climate, economic, and social scenarios (FEMA, 2019; Meulen et al., 2022)

Part tree. Nature-based coastal adaptation strategies

Nature-based adaptation strategies

Shift from hard to soft

The growing body of research related to coastal habitats restoration identifies both broader scientific and applied interest in and evidence of NbS implementation (Zhang et al., 2018; Bayraktarov et al., 2016; Smith et al., 2020). Coastal habitats provide a many ecosystem services including flood protection, eco resources, recreation, tourism, and carbon sequestration (Barbier et al., 2011; Mcleod et al., 2011; Scyphers et al., 2011; Silliman et al., 2019; Smith et al., 2020). As noted previously, the shift from hard to soft infrastructure in European practice happened in the 1980-s with the Dutch Eastern Scheldt’s salt marshes ecosystem protection augmented with a storm surge barrier closing as the high tides approach (SAEIJS, 1982; Koningsveld et al., 2008). This transition from ‘Building in Nature’ to ‘Building with Nature’ brought a valuable alternative to the traditional approach. (Meulen et al., 2022; Ecoshape, 2020)

Nature-based strategies

The ecosystem-based approach has multiple names including nature-based solutions (World Bank 2018, Somarakis et al. 2019), building with nature (Waterman 1980, de Vriend and van Koningsveld 2012), green infrastructure (European Union 2013), natural- and nature-based features (Bridges et al. 2015) or ecological engineering (Borsje et al. 2011). Regardless of nomenclature, supporting principles are comprised of the natural elements that reduce flood risk, offer recreational and health benefits, and preserve ecological values for nature and humans (van der Meulen and van der Valk 2019; Meulen et al., 2022). The growing body of research proves the effectiveness of NbS in coastal flood risk reduction (Ferrario et al. 2014; Temmerman et al., 2013; Spalding et al., 2013; Reguero et al., 2014; Bridges, et al, 2021). The advantages of soft solutions over the other measures are their conservation values, and many co-benefits including natural resource management and tourism (Groot et al. 2012; Meulen et al., 2022).

There are four major types of NbS approaches applicable for various habitats, including restoration, management, protection, and creation. Reclamation, or rehabilitation - a return to the pre-disturbance state – and the protection are the most beneficial for long-lasting ecosystem and cultural values. Creation and management involve artificial landscapes, including agriculture and farming (Shiao et al, 2020; (University of Oxford, 2019; IUCN, 2012).

Federal emergency management agency`s (FEMA`s) local governments guide provides the major types of nature-based solutions at different scales and purposes. The categories are (1) watershed or landscape scale long-term practices, (2) neighborhood or site scale (relatively compact stormwater management), and (3) coastal NbS aimed to stabilize and buffer the shoreline from storm risks. The latter is realized through a combination of natural and structural elements, such as the coastal wetlands, oyster reefs, vegetated dunes, waterfront parks, and living shorelines (FEMA, 2019). The NbS`s major types of habitats are estimated to considerably reduce the loss. As such, coastal wetlands reduced Hurricane Sandy fiscal and physical flood damage by $625 Million depending on the size and robustness of the vegetation (Narayan et al., 2017). Another meta-study of the five habitats has shown they are attenuating wave heights between 35% and 71% - salt -marshes by 72%, coral reefs by 70%, seagrass/kelp beds by 36%, and mangroves by 31%. (Narayan et al., 2016).

Hybrid coastal protection strategies

The hybrid approaches derived from the Dutch practice are also known as “building with nature” and “Living with water” (Ecoshape, 2020; Powell et al., 2019; Vriend et al., 2014; de Vriend and van Koningsveld, 2012; Aiken et al., 2014). These strategies combine natural habitats and engineered systems to realize their benefits, such as combination of levees and wetlands, or the bulkheads and ripraps or oysterbeds (USACE, 2019; USACE Nationwide Permit for Living Shorelines; the Living Shorelines Act, 2019; NOAA, 2015). They have the high potential to provide the triple-bottom line of benefits that support coastal habitats (Currin et al., 2008; Davis et al., 2015; Gittman et al., 2016b), community resilience (Manis et al., 2015; Smith et al., 2018), and cost effectiveness (Smith et al., 2017, 2018). Although, this approach needs to bring more attention to ecosystem values (Palmer et al., 2014; Smith et al., 2020).

Suitability - human and ecosystem factors of allocation

The latest knowledge on the NbS is aggregated in the International Guidelines prepared by USACE and international team of researchers (Bridges et al., 2022). The recommendations consider multiple factors that inform ecosystem-based adaptation decisions, with particular focus on their performance and endurance. These are the environmental conditions such as vegetation types, elevations, nearshore bathymetry, wave height, water levels, and aspects such as the wetland elevation and configuration. Human factors such as the shoreline embankments, infrastructural, and land use practices are less explored in relation to NbS allocation. They are mainly referred to when prioritizing adaptation measures or analyzing the effects of adaptation infrastructure on the coastal hydrodynamics. As such, inlets and exposure to the fetch affect surge-attenuation most considerably (Lawler, Haddad, and Ferreira 2016), whereas the structured solutions may cause wave refraction and scouring (Morton and Barras 2011).

Native ecosystems

The nature-based solutions should follow the natural patterns of an area to enforce sustainability of ecosystems. South Carolina shore is a lowland inhabited with wetland ecosystems. Coastal wetlands are found in intertidal zones on all continents except Antarctica.

Salt marshes dominate in temperate regions, while mangrove forests are prevalent in the tropics and subtropics. Inland, salt marshes give way to brackish and tidal freshwater wetlands. Coastal wetlands occur in low-to-moderate wave-energy settings with relatively low slope and are common along inland coasts and estuarine shorelines on soft and unconsolidated sediments, which allows vegetation to trap fine sediment particles and prevent resuspension (Bridges et al., 2021b). Grain size tends to decrease landward due to decreasing tidal energy. Brackish and freshwater wetlands have lower salinity and are found in the upper reaches of tidal influence. They are more diverse than salt marshes and mangroves, but species diversity varies by location. Tidal flats, which are adjacent to wetlands, help dissipate wave energy and play a crucial role in sediment exchanges during storms.

Performance of the NbS

No comprehensive assessment yet exists

Currently there is no sufficient method of assessing the suitable conditions and the respective effects of ecosystem-based protection. The NbS are still not broadly implemented, and the factors of a site suitability for allocating them are yet to be determined based on monitoring and modeling. (Bridges et al, 2021b)

Measuring the status of resilience

The research on resilience assessment suggests that evaluation for the adaptation actions should consider the four key parameters of actions proposed: equity, effectiveness, efficiency and legitimacy (Adger, Arnell, and Tompkins, 2004; Lorie et al., 2001; Fankhauser et al., 1999; Burton et al., 2002). Indeed, most of the high-level evaluation frameworks are based on these principles of assessment of various resilience parameters. These are four major systems of evaluation - City Resilience Framework (CRF), UNISDR City Resilience Scorecard, Climate and Disaster Resilience Index (CDRI), and NOAA Coastal Community Resilience Guide (Rose, 2007; UNISDR, 2017). UNISDR City Resilience Scorecard is one of the broad-accepted systems of tracing the progress towards resilience (NRC, 2012) criteria of management and financing, planning and disaster preparedness, hazard response ability to recover (UNISDR, 2009; UNISDR, 2017). The authors analyzed and compared their validity to generate an upgraded evaluation tool with the criteria of governance, socio-economic, resource management, land use and infrastructure, and mitigation strategies, with development of resilience plans and policies nested under the umbrella of the institutional parameter (Oktari et al., 2020).

Among the other ways to measure resilience there are social, physical, economic, institutional, natural, and disaster recovery indicators (Rubinoff & Courtney, 2007; Shaw et al., 2010; UNDRR, 2017). Most of the frameworks emphasize the importance of a comprehensive plan in pursuing the resilience of a community. The limitations of these frameworks is the focus on physical and demographic characteristics as a static variable which need to be fixed with the scenario-based approach (de Ruig et al., 2013; Kousky, 2014).

Evaluation of the adaptation measures

Measuring Nature-based protection capacity involves an array of factors such as biophysical, market and non-market economic values, qualitative wellbeing impacts, and social and institutional results. Depending on the goal, the models of NbS evaluation are subdivided into risk exposure reduction, biophysical effects, economic effects, livelihood and wellbeing, social and administrative outcomes (BMUB, Emerton, 2017). The major criteria are effectiveness of the capacity to achieve a goal of sustained reduction of risk, and efficiency of resources invested (Jones, 2001; Ingham and Ulph, 2003), in terms of costs and benefits of both reduced impacts or enhanced opportunities (Adger, Arnell, Tompkins, 2004). The damage reduction needed to assess the effectiveness include direct physical damage and indirect market and economic losses in the local or regional scale (Costanza et al., 2008). These categories added with private- public costs and benefits of actions and compared with no action scenario provide the basis for economic efficiency evaluation of the adaptation strategy (Adger, Arnell, Tompkins, 2004).

Ecosystem performance

An adaptation solution should focus on performance aspects that are controlled within the design, such as vegetation types and surface elevations. Further optimization of the FRM (Flood Risk Management) functions of an ecosystem can be adjusted based on the specific settings and design storm characteristics. Flow reduction, waves, and surge attenuation that wetlands provide are related to vegetation parameters such as height, density, flexibility, and roots ratio. The platform elevation, tidal channel inlets and other structural parameters are easier to control. Storm and geomorphic characteristics are also affecting attenuation performance of ecosystems. The assessment of these effects is based on observation and modeling. (Bridges et al., 2021 b).

Observation-based metrics

NNBF guides utilize several international studies in measuring ecosystem factors and performance, mostly based on observations and modeling. They are the main source of the various NbS protective parameters (Bridges et al., 2022). For instance, the latest Louisiana 2023 Coastal Master Plan is based on the Coastal Reference Monitoring System data. The CRMS is a network of over 300 observation stations that collect data on wetland elevation, water levels, salinity, vegetation, and land change. It has been used to refine the model for wetland vegetation response to changes in salinity and inundation stress, as well as to improve the evaluation of subsidence across the coast. The hands-on research on ecosystem restoration conducted by

NOAA in Texas and Maryland refined the performance parameters of living shorelines (NOAA, 2021). An ongoing NCCOS project aims to evaluate the long-term performance of three types of nature-based solutions: coastal wetlands, oyster reefs, and coral reefs, to understand their range of environmental conditions for providing coastal resilience benefits (NCCOS, 2022).

Latest modeling approach

The latest knowledge on ecosystem-based solutions collected in the NNBF Guidelines (Bridges et al., 2021) is based on both the observations and modeling of the NbS. The models that are referred to in the guidelines include such approaches as hydrological, habitat suitability, and GIS-based. Their principles and major applications are compared in Figure 02. The most flood affected US regions recently applied proposed restoration for the deltaic areas to mitigate the adverse impacts of intensive land uses. The Louisiana 2023 Coastal Master Plan focused on protection of key community assets with the habitats (CPRA, LA, 2023) and USACE Charleston peninsula study (USACE, 2021) are the examples of the recent modeling approaches. The tools used for these plans are also compared in Table 02.

Table 02. Types of models to assess the NbS`s performance

Type	Principles	Name	Source	Limitations
Hydrological	The effectiveness of wetland restoration or floodplain reconnection in reducing flood levels	HEC-RAS	U.S. Army Corps of Engineers, 2016	Technical modeling tool – lacks ecological and socioeconomic processes considerations, geomorphologic simpliicity
		SWAT	Neitsch et al, 2011	
GIS-based	Analyze flood risk and effectiveness of NbS against them	FEMA Hazus	FEMA, 2017	Focuses on the physical impacts of natural hazards
		NRCS's WinTR-20	USDA, 2011	Simplistic representation of

				land use and land cover
Habitat suitability	Coastal Vulnerability module estimates the ecosystems risk reduction effectiveness. Generates Exposure Index ranks	InVEST	Sharp et al., 2016	Complexity and lack of flexibility of inputs
	Potential of natural systems to attenuate the flood based on flood levels, vegetation coverage, and other environmental variables, collected from field studies and remote sensing	Hydrologic Landscape Regions	USGS, 2011	Limited consideration of coastal systems, Focus on water quantity rather than quality
Mathematical	Modular, compartmental approach that allows for the integration of different models and data sources. Simulates the interactions between different components of the coastal ecosystem	Integrated Compartment Model (ICM)	CPRA, Louisiana, 2023	Does not measure the desirable variable of flood levels reduction by a given ecosystem
	Evaluates the potential impacts of a range of factors, including sea level rise, storm surge, riverine flooding, and wetland loss	CLARA	CPRA, Louisiana, 2023	Specific numeric values of flood levels reduction will depend on the specific project and location
Integrated	Coastal hazards modeling system that was used to assess the impacts of sea-level rise and storm surge on the Charleston Peninsula.	CoSMoS	USACE, 2021	Does not explicitly consider the ecological or social dimensions of NbS
	Economics of Climate Adaptation framework evaluates the effectiveness of nature-based solutions: climate risk; the extent future economic growth exacerbates this risk; and incremental loss under various climate scenarios.	CLIMADA, ECA	Reguero et al., 2014; Bresch, D. N., Franke, J., Frank, C., & Huggel, C. (2018)	Limited consideration of ecological factors, based on large-scale datasets -loss of detail at a local scale

The NNBF also incorporates data on the physical properties of the ecosystem, such as soil type, elevation, and slope, as well as information on the location and design of the restoration or protection project (Bridges et al., 2021b). All these models should be refined with expert knowledge and judgement, which supports the reliability of the data. (Berman et al., 2007)

Flood mitigation and other adaptation capacities

The major protective benefits of coastal ecosystems are the reduction of chronic inundation and storm surge waves attenuation (UCSUSA, 2017; Bridges et al., 2021b; Reguero et al., 2014). Several recent studies on the role of coastal wetlands in flood protection point at the importance of both natural and human factors – fiscal values, wetland coverage, coastline shape, elevation, building codes, and the probability of experiencing different wind intensities. (Sun& Carson, 2020). The attenuative capacity of NbS against surge waves is explored based on the coastal geomorphology and vegetation characteristics.

The reduction of storm surge waves along a river or estuary depends on the depth and width of the waterway, the slope and roughness of the riverbanks, the shape and alignment of the river channel, and the storm magnitude. The frictional resistance of the riverbed and banks can absorb and dissipate kinetic energy of the storm surge waves. The slope or gradient of the river or estuary bed can influence the speed, direction, and distribution of flow and surge energy. The steeper river slopes enhance the dissipation of the wave energy, while flatter slopes can allow the wave to travel further inland. The shape and alignment of the river channel can create complex wave patterns, such as reflections, refraction, and standing waves, which can amplify or attenuate the storm surge waves at certain locations. This effect is particularly important in narrow and winding rivers, where the wave energy can be trapped and resonated, causing more severe flooding and erosion (Bridges et al., 2021b, Reguero et al., 2014).

Surge waves affecting coastal areas also interact with the shoreline vegetation to diffract and reduce the energy along with the distance from estuary. As storm surge waves move from the open sea towards the land, they encounter increasing friction from the sea bottom and coastline, which resists them. Areas with wide and deep estuaries or low-lying coastal plains can act as natural buffers and dissipate the storm surge energy, reducing the risk of flooding and damage (Bridges et al., 2021b). As discussed earlier, various types of NbS and hybrid solutions have different levels of flood reduction, based on their location, structural, and vegetation characteristics. They perform differently considering non-linear "sponge" attenuation properties of "living" part of a shoreline. For instance, mangroves reduce wave heights by up to 66%, with the greatest reductions observed for shorter wave periods (Alongi, 2008; Barbier et al., 2008). A study by Donnelly et al. (2016) found that dunes can reduce wave heights by up to 60%, with the greatest reductions observed for low-energy waves. In terms of storm surge reduction, a study by Zhang et al. (2020) found that dunes can reduce storm surge heights by up to 5 ft.

Parameters of various ecosystems

The slope, height, and vegetation of the living shoreline are the essential design considerations informing the capacity to mitigate the risks. (Bridges et al., 2021b; Beck et al., 2018). The dimensions of living shorelines recommended by the literature vary, but a width of at least 50-100 feet is recommended. A dike with a crest height of 12-15 ft can reduce wave height by up to 90% (Kok et al., 2015). Horizontal levees of 6-10 ft height and of 50-100 ft width are effective for wave and storm surge attenuation both in their structural and vegetation-based protection (Currin et al., 2019). Reguero et al. (2014) found that a barrier island with a width of 300 - 700 ft and elevation of 9-12 ft can provide up to 90% reduction in wave height and 50-70%

reduction in storm surge. The effectiveness of a breakwater will depend on its size, orientation, and distance from the shoreline, though Li et al. (2017) found that an island 1800 ft to 30 ft provides up to 50% reduction in wave height. Temmerman et al. (2013) found that salt marshes can reduce wave heights by up to 80%, with the greatest reductions for long wave periods, while Möller et al. (2014) found that they reduce storm surge by up to 5 ft. The effectiveness of these NbS`s depends on many factors beyond wave and storm surge reduction, such as their ability to adapt to changing climate conditions, cost-effectiveness, and specific site conditions.

Part four. Economic impact of NbS

Floods and especially coastal floods cause the highest damage among other natural hazards. The 2017 hurricane season was the most destructive in US history with $265 billion in flood, rain, wave, and wind damage, and over one million people evacuating homes. (Kousky et al., 2021; Gall et al., 2011; Smith and Katz, 2013). The monetary approximation of protection value from ecosystems is needed to inform communities of their significance (Costanza et al., 2014). Multiple studies discuss the cultural, social, ecological values of ecosystems (Baveye, 2014; Chan et al., 2012; Baveye et al., 2013; Fish et al., 2016; de Souza Queiroz et al., 2017; Bryce et al., 2016; Irvine et al., 2016; Jax et al., 2013), accepting that some ecosystem values are proper to quantify, while some non-monetary values are better described qualitatively in individual utility, willingness to pay, or other terms (Folkersen, 2018). The dynamic economic impacts of coastal risks and damages are not well explored, whereas a greater knowledge about vulnerability and potential of coastal areas will bolster a strong argument for adaptation strategies, as a greater share of the population is exposed to natural disasters (Changnon et. al. 2000; Rappaport and Sachs 2003; Pielke et. al. 2008; Deryugina, 2011; Boustan, et al., 2017).

Impact assessment frameworks

The literature on the economic effects of flood hazards focuses on multiple elements of local financial flows and market signals. Shi and Varuzzo (2020) explored the fiscal stress of SLR on property taxes and related land-use policies. The methods to quantify impacts on economic activity include out-migration rates, housing prices and rents, local productivity and labor demand (Boustan, et al, 2017; Martinich & Crimmins, 2019), footprints of coastal development alteration (Lorie et al., 2020; Neumann et al., 2015; Neumann, Chinowsky, Helman et al, 2021; Dell et al., 2014; Cavallo et al., 2013; Hsiang & Jina, 2014; Burke et al, 2015; Cattaneo & Peri, 2016; Kocornik-Mina et. al., 2021), and potential revenue growth (Cavallo et al., 2013). Another factor is the direct damage losses of infrastructure and properties under different coastal management approaches (Neumann, Chinowsky, Helman et al, 2021).

The dynamic economic impacts of coastal risks and damages are not well explored, whereas there the economic vulnerability of coastal territories bolsters the need in adaptation, as a greater share of the population is exposed to natural disasters (Changnon et. al. 2000; Rappaport and Sachs 2003; Pielke et. al. 2008; Deryugina, 2011; Boustan, et al., 2017). The methods to quantify impacts on economic activity include out-migration rates, housing prices and rents, local productivity and labor demand (Boustan, et al, 2017; Martinich & Crimmins, 2019), footprints of coastal development alteration (Lorie et al., 2020; Neumann et al., 2015; Neumann, Chinowsky, Helman et al, 2021; Dell et al., 2014; Cavallo et al., 2013; Hsiang & Jina, 2014; Burke et al, 2015; Cattaneo & Peri, 2016; Kocornik-Mina et. al., 2021), and potential revenue growth (Cavallo et al., 2013).

Coastal ecosystems economic valuation will be better determined using multi-criteria assessments (Samonte-Tan et al. 2007: Conservation International, 2008) that involve ecological balance, lower maintenance, a healthier environment, synergy with mitigation, or an extended life expectancy (Meulen et al., 2022; Baills et al., 2020). Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) – briefly discussed in previous literature strand - is a software broadly applied to NbS evaluation. There are many other means of economic dynamics evaluation, including Economics of Climate Adaptation (Reguero et al., 2014), and disaggregated quantitative approaches to measuring performance (purchases, sales, production, investment, income, employment, etc.), or macroeconomic changes (GDP, property values, inflation, human capital, etc).

Economic benefits

Different techniques are used to evaluate NbS in terms of financial and economic benefits, including Cost-benefit analysis, Cost-effectiveness analysis, Least cost analysis, Value for money, Input-output, General/partial equilibrium models, etc. The indicators measured include net present value NPV, internal rate of return IRR, benefit-cost ratio BCR, return on investment ROI or cost-effectiveness ratio CER (Emerton, 2014). Several economic models are discussed - hedonic models estimate the use value to property owners and tenants, while travel cost models focus on recreational use value of nature, as realized by residents and visitors. Among the economic assessment tools commonly used are cost-benefits ratio analysis, price analysis, and willingness to pay (Narayan et al., 2016). Some overlap is observed between these estimations, as reflected in residents WTP to live near those resources (Johnston et al., 2001; Hagedoorn et al., 2021).

CBA is accessible and uniform, though not always an optimal assessment method (FEMA; NCPM; Lorie et al. 2020; Neumann et al. 2015; Neumann, J.E., Chinowsky, P., Helman, J. et al, 2021). It is focused on the costs and benefits of a NBS over a time period of mitigation action's effectiveness, normally around 25 years for the conventional infrastructure, and those of its alternatives (Atkins & Mourato; 2015; Raymond et al., EWD, 2017). It is an evidence-based framework that can be used to evaluate a NBS and grey alternatives enforcing the rationality of resource consuming decisions (Sartori et al., 2014; Boardman, 2014). An extensive body of research tested its application at different scales, measuring the outputs: NPV, the BCR, and the internal rate of return (Zerbe and Dively 1994; Dasgupta and Pearce 1978; Mechler, 2003; Campbell and Brown 2003, National Research Council 2004, Moore and Thorsnes 2007). CBA is widely practiced providing a framework for comparison and assessment of federal legislation, grants, and decision-making. Future costs and benefits are compared under a criterion, determining whether monetary benefits exceed costs. The major components prescribed by USACE CBA standards are listed in the Table 03.

Benefits in this model are more often computed as avoided damages and sometimes indirect benefits for economic activities as aggregated values. The assessment is not directly applicable to NbS, as its solely quantitative assessment results in the false sense of confidence, omitting the quality parameters (Stokey and Zeckhauser 1978, Boardman et al. 2001). It also lacks the internal rate of return, causing imbalance of transfers and distribution, and fails to support the comprehensive nature of solutions (Godschalk et al., 2009). Another issue is a proper discount rate value choice that adequately accounts for future benefits. It also depends on the macro-economic and geographic context (Onofri, Nunes, 2020; FEMA, 2019;

Cost/Benefit Item	**Alternative 2**
Investment Costs	–
Project First Cost	$1,133,000
Interest During Construction	$130,000
Total Investment Cost	$1,269,000
Average Annual Cost[1]	–
Average Annual First Cost	$42,500
Annual OMRR&R[2] Cost	$3,000
Average Annual Costs	$45,500
Benefits[1]	–
Average Annualized Benefits	$493,000
Net Benefits	$447,500

Table 03. CBA, USACE, 2022

USACE, 2019; Raymond et al., EKLIPSE, 2017). The impact chains can have interdisciplinary scenarios, complicating calculation (Kumar et al., 2021). Some of the CBA frameworks (e.g., Boardman, 2014; Pearce et al., 2006) address this uncertainty with Monte-Carlo simulations, sensitivity analysis, best-worst case analysis, etc. (Kumar et al., 2021).

Coastal habitats directly benefit communities by flooding and erosion mitigation, and the assessment of their costs and benefits must involve the full range of factors (Arkema et al., 2015; Barbier et al., 2013; Möller et al., 2014; Narayan et al., 2017; Spalding et al., 2014). Indicative and project costs include the up-front investments, capital expenditures, land, equipment, materials, and infrastructure; labor costs for construction, operation, and maintenance. There is a small but growing evidence on the real maintenance costs of different habitats, with the assumption that nature supports its lifecycle mostly without anthropogenic interventions. There must also be considered transaction costs for performing the payments and involving investments, design, negotiation, and insurance costs, opportunity costs for implementing the investment portfolio (WRI, 2019). The benefits of NbS can be subdivided into direct economic benefits and indirect, or co-benefits. (WRI, 2019)

The market tends to rely on traditional approaches - engineering solutions, restoration is not taking place at the needed scale. (Bloomberg, Pope, 2017). Meanwhile, conventional metrics can hardly explain the potential of resilient infrastructure financing, as it doesn`t generate cash flows directly, doesn`t yet provide predictable savings, and is supported with low and often exempt taxation, limiting rates of return (Spanger-Siegfried et al., 2017).

Direct loss prevented

Physical impacts on capital stock such as infrastructure, structures, and machinery are estimated on different scales (Mechler, 2003). USACE provides direct damage functions for various construction uses to identify the percent of a replacement value per flood depth intervals. (USACE SACS, 2022). Structure uses are associated with HAZUS occupancy classes and replacement values (BRV) and contents-to-structure value ratios (CSVRs). These aggregated data can be replaced with the state or local resources for improved accuracy (FEMA BCA, 2011). The efforts to assess the value of habitats are challenging due to many uncertainties and focus on the instrumental value more than on the intrinsic. Resource extraction, agriculture, and energy production face monetary losses due to coastal extreme events. The damage to coastal communities as a result of losing ecosystems' flood mitigation capacity is associated with the average $33,000 damage per loss of 1 ha of wetlands, and three to five properties ($590,000 - $792,000) for a 0.1 loss of a wetland-water ratio (Costanza et al., 2008; Barbier et al., 2013).

Indirect loss prevention

The mitigation of direct damage consequences on production, revenue, and human capital after business interruption is expressed with the indirect loss prevention (Mechler, 2003). There are case studies in the aftermath of the major hurricanes (Lopez, 2009; Basker; Graveline;Herrera et al., 2014), providing the data for the pre-disaster estimations. The literature on the broader medium-term effects in the aftermath of disasters and accordingly – the benefits in case of the protection and minimizing these adverse impacts (Barbier et al., 2013; Arkema et al., 2013; Herrera et al., 2019) – consider population movements, labor market changes, government spending in post-disaster economics, technological progress, and induced productivity growth. The case study based research show the post-disaster economic dynamics expressed in growth of earnings in Florida (Belasen and Polachek, 2008), local employment rates decline in Louisiana (Brown, Mason, and Tiller, 2006), lower per capita income growth in general for the coastal counties (Strobl, 2008), population, employment, wages, and transfers to individuals from safety programs over years following the disaster (Deryugina, 2011). Intangible assets and indirect damage assessment are hard to verify with high probability levels due to the size of the impacts and resiliency of the economy (Rose, 2004; Kousky 2014). The broader array of risks prevented by NbS includes economic damage, water quality and availability, productivity and availability of aquatic species, business associated with natural resource management productivity, beaches and other important recreational and commercial functions, and endangered species protection.

Co-benefits, welfare opportunities, and growth

Co-benefits are essential for the analysis to allow better understanding for potential co-investors, change the optimal prioritization, return on investment (ROI). They need to be described at least qualitatively to allow a more holistic view for stakeholders and engage additional beneficiaries. (WRI, 2019). Coastal proximity, the capital, labor, and transportation benefits as the result of hybrid protection include reduction in commuting delays about 70% among the highest earners (Hauer et al. 2020). Resilience-induced technological progress, new jobs, and consequent productivity growth is discussed in the smaller strand of recent literature (Raes et al., 2021; Lieuw-Kie-Song and Pérez-Cirera, 2020). Additionally, there is evidence of ecological and social capital harnessing and other jobs creation in the ecosystem services and recreation tourism (Lavorel et al., 2020).

Ecosystem services

Ecosystem services define the contributions of ecosystem operation to communities well-being. (Burkhard et al., 2012; Raymond et al., 2017), recreational or cultural values (Kabisch and Haase, 2014). Coastal habitats provide social benefits of carbon sequestration, nutrient cycling, sustaining biodiversity, tourism and recreation (Agardy, 1993; Barbier et al., 2013; Beck et al., 2018; Beck et al., 2001; Duarte, 2017; Guerry et al., 2012; Pendleton et al., 2011; Barbier et al., 2013; Costanza et al., 1997). Cultural, recreation, aesthetic, health, bequest, and tourism values are evaluated by the WTP surveys and participatory planning (Brown and Fagerholm, 2014; Haase, 2015; Iacob et al., 2014; Kati and Jari, 2016; Keeley et al., 2013; Raymond et al., 2009; Raymond et al., EKLIPSE, 2017), aggregated market and non-market valuation techniques (Bergstrom et al., 1990; Schuster & Doerr, 2015; Duraiappah et al., 2005; Ghermandi et al., 2009; Sandifer & Sutton-Grier, 2014; Wedding, 2022). Schuster and Doerr (2015) summarize the range of methods used for ecosystem services evaluation in the related guide: market price, productivity, avoided costs, substitution costs, travel cost, hedonic property value, contingent valuation, choice experiment, and benefit transfer.

The investigation of the economic dimension of resilience in the international experience has a potential to implement the framework solutions in the countries not yet committed to sustainable development goals and gradually switching to environmentalism paradigms from resource management approach. (Neumann et al, 2021). The natural value of coastal wetlands provides $23.2 billion annually in storm protection services, while a loss of 1 ha corresponded with storm damages of $33,000 (Costanza et al., 2008). Another study on Louisiana shows that an 0.1 increase in the ratio of wetland reduce storm surge risk in saving three to five properties estimated between $590,000 and $792,000 (Barbier et al., 2013). A few studies quantified the value of natural ecosystems and hybrid approaches in coastal adaptation. Ecosystem services for coastal communities, fisheries, biodiversity, water quality, recreational and cultural benefits, and carbon sinks all create added value accounting for the future growth (Barbier et al., 2011; Nellemann et al., 2009; Serrano et al., 2019; Moraes et al., 2022).

Potential economic growth and added value

For the US, NOAA reports 45% GDP generated by the coastal counties, whereas the EU Blue Growth report indicates over 5 million jobs generating EUR 500 billion annually, and a global ocean economy of EUR 1.3 trillion (Jarratt & Davies, 2020). Shoreline counties contributed $6.6 trillion to the U.S. GDP approximating the half of the total numbers (NOAA, 2012, Sutton-Grier, Wowk, Bamford, 2015). One of the tools to evaluate the NbS added value is input-output analysis with a matrix of a region's economy indicators, which predicts the implementation effects for different industries. The greater the interdependence among industry sectors, the larger the multiplier effect of the economy (USACE, Charleston District, FR-EIS, 2022). The load and value of tourism and recreation are high and vulnerable in the coastal cities. The United Nations estimates that "approximately half of tourists visit a coastal area" (UNWTO, 2013; Jarratt and Davies, 2020).

Tourism and recreation benefits are considerable for the coastal cities' economies in generated jobs, revenue, and hotel development. They can be estimated based on revenues and earnings, while considering spillover negative impacts on tourism from hard infrastructure. The study assessing the effects of coastal protection in Monterey, California, discovered the major co-benefit of protection of recreational values improved with ecological conditions created. This used several metrics of market and non-market services and the benefits transfer model. A relative value ranking of different parts of the shoreline provided the full picture of recreation scores based on the physical, biotic, and cultural conditions of the segments. (Emerton, 2014). The list of values that NbS are accounting for is shown in the Figure 01

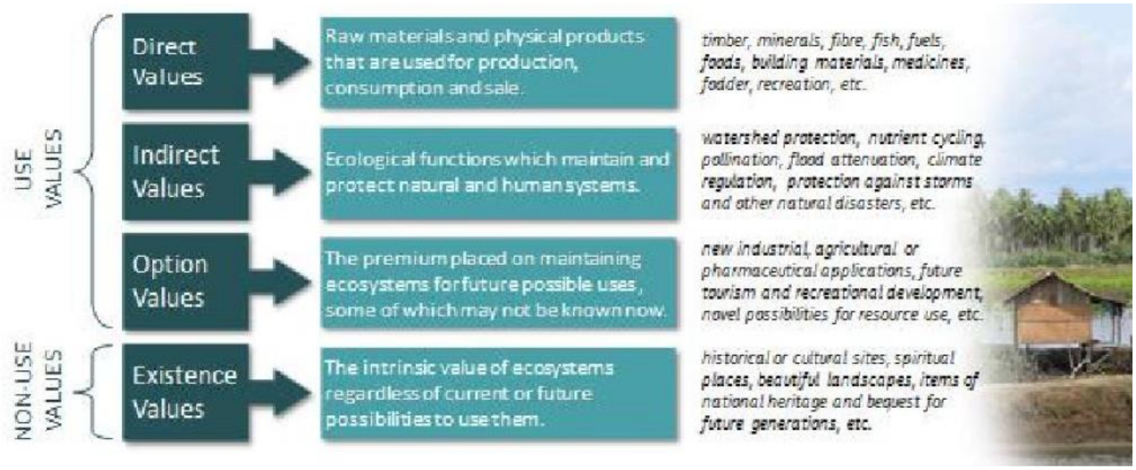


Figure 01. Total economic value of coastal ecosystems (Emerton, 2014, p. 5)

Approaches to evaluate the co-benefits are either formal economic modeling - income accounting, ecosystem accounting, input-output analysis, equilibrium models - or more flexible trend estimation of economic impacts applicable at many scales (Emerton, 2014). Travel Cost Model assessing the value through the number of recreational trips to a specific site multiplied by a cost of traveling and comparative costs of alternative travels, and the quality of the recreational experience (Freeman, 1993; Johnston et al., 2001). The total environmental value TEV method comprises use - water supply, flood control, fishing, and tourism - and non-use values - separate from community's utility, existence, bequest for future generations, and option values of the future use of resources. Contingent valuation method (CVM) was used to value non-market goods, and the willingness to pay (WTP) ensured steady flow of ecosystem services. This method estimates perceived values of the ecosystem services. Recreation values were estimated from the revenues and costs data from local tourist operators in a study area, while the benefits generated by the flood risk reduction were calculated using the damage costs function from previous floods and scientific projections. (Baig et al., 2016).

Integrated assessment models

IAM models in coastal and climate adaptation assessment embrace climate and economic models to address the relationship between economic activity, GHG emissions, and global temperature rise (Nordhaus, 1994; Hope, 1993; Tol, 1995; Revesz et al. 2014; Houser et al., 2015). They simplify the climate and economic aspects of systems to assess the emission reduction levels correlated with specific GDP (Kopp &Mignone 2012). The research states the importance of integration while distinguishment between different economic sectors (Conway et al. 2019; Frame et al., 2020; Kousky et al., 2014).

More flexible analysis tools are intended to accommodate and resolve the issues of time and extent, assessing feasibility of changing options and projections uncertainty (Hunt and Watkiss, 2011; Kunreuther et al., 2014). Further, studies applied a scenario-based assessment of adaptation over time (Aerts et al., 2014a; Mechler, 2003). Adaptation pathways method of De Ruig (2019) with multiple scenarios for delaying expenditures or accelerating investments by private sector involvement (De Ruig et al., 2019) provides flexible and receptive assessment tool needed for climate resilience planning economic support (Kousky et al., 2014).

Literature summary and research gaps

The literature that I analyzed placed my research question in a broader context of the current issues to which coastal cities are expected to be exposed in upcoming decades, as well as the methods to address them on the local and regional scales. The major climate change threats and scenarios help to reveal the global trends and regional variety of risks affecting planning for coastal adaptation. Most of the states currently plan for medium and high-emission scenarios depending on the importance of communities' assets. The major threats on the Atlantic coast include coastal storm surge and sea level rise. The levels of these risks are unidentified due to the multitude of local conditions. My research contributes to this gap using open-source data and scenario-based approach integrating the latest projections of Kopp et al. (2017) and adaptive approach of Aerts et al. (2021)

The questions of coastal vulnerability and resilience in the face of rising seas, storm surge and tidal floods are different depending on the research vista. Nevertheless, a comprehensive approach to coastal resilience involves all three levels – social equity, ecosystem protection, and economic development. I take this approach in building my methodology to enforce the long and effective lifespan of a strategy. Hazard adaptation and mitigation planning are comprised in the ecosystem-based approach to provide an array of tools to protect against the growing threats (Reguero et al., 2014, Arkema et al., 2013, Barbier et al., 2013).

The specific literature strand dedicated to Nature-based solutions is the main subject of my research, including their application in different conditions, evaluation techniques, and implementation tools and gaps. These studies reveal the metrics to assess their effectiveness, alternative solutions, implementation, and barriers arising on the different stages of their development. Limited number of cases and the gaps in their financing are among them (Kousky et al., 2014; Bridges et al., 2021b).

The evaluation metrics of Nature-based solutions show the variety and non-uniformity of the resilience assessment techniques due to the complexity of monetary and non-monetary values that nature provides. The standard economic models such as CBA, or Input-Output analysis might be applied under certain conditions and can reflect their partial representation of a real value. NbS implementation should be supported with more robust economic assessment tools (Emerton, 2014; Bridges et al., 2021b; FEMA, 2016).

Research gaps

I identified a number of research gaps based on the literature review. They are related to the complexity of projections for sea level rise, as they depend on many factors. Scientific uncertainty also relates to the full range of the effects induced by different types of green and hybrid coastal adaptation. There is a need for further research of their effects on ecosystems, societies, and economies of both the protected and contingent areas. These are the major underestimated risks of any intervention due to the negative feedback loops. There are also such unanswered questions as the metrics of performance and economic impacts of NbS, and complexity of interests and tradeoffs depending on location. I aim to address these gaps with developing a methodology and modeling of the local impacts of ecosystem-based solutions.

Globally acknowledged emission patterns and sea level rise contributors, including ice sheet melting, keep being updated. It defined the factors of uncertainties such as the rates and magnitudes of storms, locally identified water levels, land subsidence, and sediment transport patterns. It is essential for my research to consider these uncertainties in the research design, as they pose significant barriers against implementation of coastal resilience strategies. Another knowledge gap in flood exposure literature is the impacts on the commercial facilities as opposed to residential development. I contributed to these with a scenario-based model involving the latest knowledge on the sea level rise and extreme storms projections and identifying their significance for a sector of interest. There are several findings in the research on NbS implementation barriers and maladaptation, including research, design, institutional, and social factors (Laurian et al 2004; Laurian et al 2010; Carmona, 2007; Carmona and Sieh, 2004; 2005; 2008; Brouwer et al, 2013). They emphasize the need for collaboration across the stakeholders, data quality, and monitoring of results. I contributed to this research by developing an adaptive assessment model that facilitates public engagement and furthers investment in framework design.

Little or no studies address both natural and man-made factors to guide a proper NbS suitability assessment. Urbanization affects the shore through allowing or preventing habitat migration and natural sediment transport. Shoreline type and land use intensity determine the human-induced factors and dynamics of allocation suitability. On the other hand, habitat allocation, SLR and coastal storm surge depths, seabed slope, sediment accretion and erosion trends are the physical factors affecting the shoreline`s capacity to provide ecosystem benefits. In my study, due to the data accessibility and research vista, I identified areas suitable for NbS allocation by combining ecosystem and economic factors.

I also identified a lack of comprehensive metrics of NbS’s performance. According to studies, storm surge attenuation of green and hybrid solutions vary depending on the design and location. (Bridges et al., 2021b; Currin et al., 2019). Specific design considerations depend on factors such as the available space, the required level of protection, and specific site conditions. I incorporated the existing knowledge on ecosystems performance against flood risks based on their recommended crest height and slope with corresponding attenuation. My results are contributing to the gap in NbS performance assessment.

Another set of gaps is related to funding and economic impacts. The economic dimension of climate resilience is dictated by considerable tensions between flood mitigation and development, enhancing density in vulnerable areas and consequently exacerbating risk magnitude (Malecha et al., 2018; Berke et al., 2015; Berke et al., 2018). There is an ultimate need in diversification of coastal adaptation funding, as coastal areas are expected to be exposed with the growing magnitude, and more cities are facing climate risk-related budget constraints.

(Levy & Herst, 2018; USCUSA, Spanger-Siegfried et al., 2017). The opportunities of private investments attraction, market incentives, and hybrid collaborations are seen as a vital direction in view of growing threats (Levy & Herst, 2018; Kousky, 2014; Macintosh, 2013; Neumann, J.E., Chinowsky, P., Helman, J. et al, 2020; Barbier et al., 2013). To attract more private investments, the economic assessment framework needs more transparency. My study contributes to better understanding of the NbS benefits for the local business through innovative and accessible economic impact modeling.

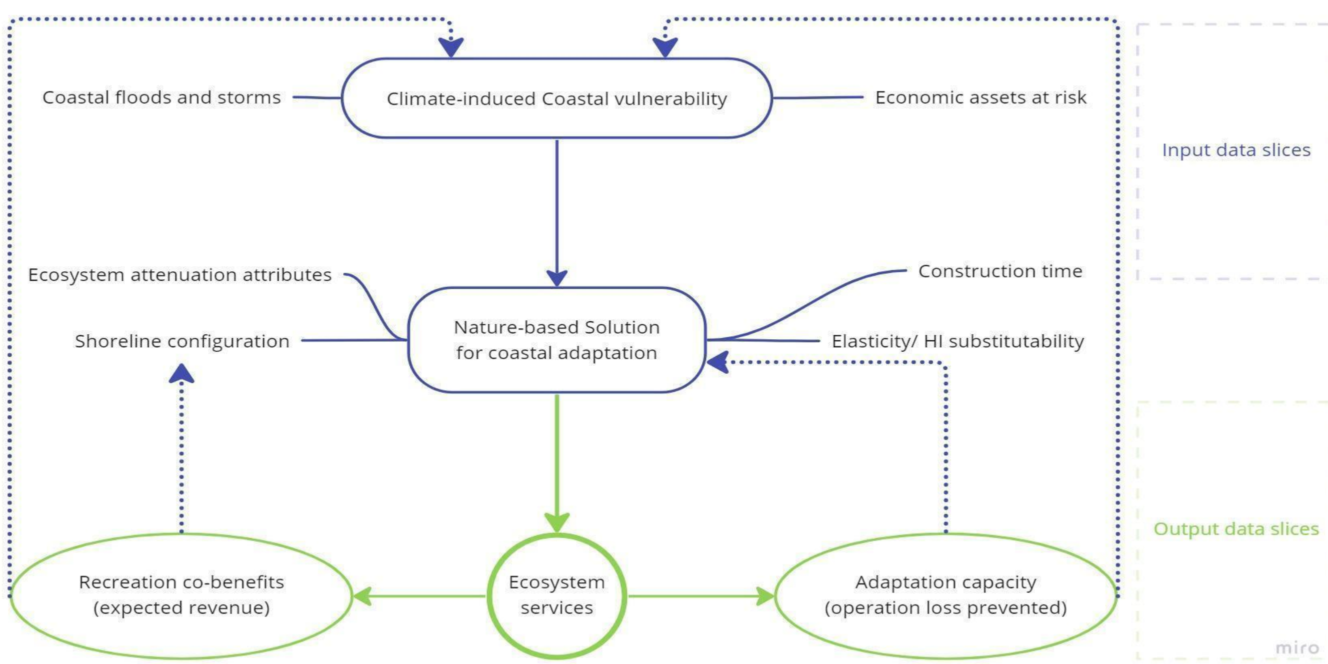
Complicated and data-heavy cost-benefit assessment limits understanding of the real values of the ecosystem-based adaptation especially under scientific uncertainties (Davis et al., 2015; Temmerman et al., 2013; Narayan et al., 2016; Morris et al., 2018; Moraes et al., 2022). My study took a separate module from the standard FEMA Hazus CBA, and introduced the weighed ranking of the recreation attractiveness to account for ecosystem services provided by ecosystem-based coastal adaptation. (Wharton, 2020). I also incorporated a scenario-based approach with the goal of addressing sea level rise and socioeconomic uncertainties.

CHAPTER TWO

METHODS

The focus of my research is nature-based adaptation strategies for the urban coastlines and their synergy with recreation and tourism economic sectors. Following the literature review takeaways, I assume that this type of protection and this land use and occupation class have a high potential for long-term coastal resilience. A balance of environmental, economic, and social goals for public welfare is essential for long-lasting ecosystem-based strategy in the coastal cities. “Designing with water” approach supports this assumption with a double-duty - multiple benefits principle (Aiken et al., 2014). The method, as shown in Figure 02, is subsequently tailored to the assessment of combined goals and includes ecosystem benefits and economic risk reduction assessment. The method and model are targeted to approximate the economic values of NbS`ecosystem benefits delivered to retail, entertainment, and lodging within a study area.

Figure 02. Simplified research design model



I built my research upon several recent studies of climate change, hazard risks, nature-based solutions, and ecosystem benefits. The methods and tools of the ecosystem-based adaptation assessment benefits discussed in the Literature review either utilize national-level observation-based correlations (Arkema et ql., 2013; Langridge et al., 2014; Narayan, 2018), regional input-output assessment for broader projection of the economic effects of NbS (Reguero et al, 2014; ECA, 2020), or cost-benefits analysis focused more on the physical characteristics of adaptation solutions and community assets. Here I built upon the Hazus model to design an assessment algorithm that should be easy to apply in other areas on the scale of implementation.

I used the Adaptation pathways approach introduced and applied by Aerts et al. (2018) for adaptive scenario-based planning allowing to navigate adaptation under scientific uncertainties. I simplified scenarios to the two types of flood risks – sea level rise and coastal storm surge – as the most likely and most extreme hazards affecting the coasts. Their impacts and relative adaptation were assessed within two timeframes for the moderate and high-emission scenarios RCP 4.5 and RCP 8.5 (IPCC AR 6, 2021). The model generated perimeter nature-based adaptation strategies that vary over scenarios to accommodate the changing risks. The areas to assess these effects were subdivided based on the current and future land uses.

Area and focus of study

Area of interest

I based my study in Charleston, SC, as the city among the most affected by the major floods with even more concerning future projections. According to the Union of Concerned Scientists report (2017), the number of flood events for this area is projected to increase from an average of 11 flood events annually in 2005-2014 to 180 flood events per year by 2035 under a high sea level rise scenario. These inundation events are defined as flooding of at least 1.5 feet above the local high tide line. It makes Charleston the fourth most affected by chronic inundation county in the US according to this report (Spanger-Siegfried et al., 2017).

Charleston Historic Center – Peninsula - matches the economic impact assessment goals of my research. Its economy is represented significantly by the tourism sector located and partly dependent on the coastal areas. In 2019, the tourism industry generated over $9.7 billion in economic impact in the Charleston region, supporting over 50,000 jobs and providing over $2 billion in wages and salaries (Charleston Area Convention and Visitors Bureau). The historic downtown of Charleston is a popular tourist destination, with attractions such as the city's historic homes, gardens, and plantations, as well as its dining and shopping options. Additionally, the area's beaches, waterways, and outdoor recreation opportunities also draw many visitors to the region.

Army Corps of Engineer Peninsula Study

The city of Charleston is actively involved in developing coastal flood protection strategies to reduce the exposure of peninsula and its multiple cultural assets to the coastal floods. A highly detailed retention wall USACE proposal is based on the flood impacts assessment and feasibility study (USACE, 2015; USACE, 2020; USACE, 2021). Areas with higher population density, commercial and industrial areas, and most vulnerable to flooding were given priority. The study used LiDAR data to determine the vulnerable areas based on the elevation, FEMA flood zone maps to identify the risk of flooding, and historical flood data to identify areas that have experienced flooding in the past. The GIS and census data identified the critical infrastructure, lower-income populations, and areas with higher population density. Flood risks considered in the study are based on the NOAA (See Table 04), storm surge scenarios, tidal flooding, and rainfall historical data.

Gauge Status: Active and compliant tide gauge
Epoch: 1983 to 2001
8665530, Charleston, SC
NOAA's 2006 Published Rate: 0.01033 feet/yr
All values are expressed in feet relative to LMSL

Year	USACE Low	USACE Int	USACE High
1992	0.00	0.00	0.00
2002	0.10	0.11	0.14
2012	0.21	0.24	0.36
2022	0.31	0.39	0.64
2032	0.41	0.56	1.01
2042	0.52	0.74	1.44
2052	0.62	0.94	1.96
2062	0.72	1.16	2.54
2072	0.83	1.40	3.20
2082	0.93	1.65	3.93

Table 04. Estimated sea level change according to NOAA and using the USACE Sea-Level Change Curve Calculator.

The study then proposed a combination of hard and soft infrastructure solutions to enhance the resilience of the Charleston Peninsula based on the flood risks and economic impact assessment modeling. The hard infrastructure solutions include a floodwall system with a height of up to 11 feet in some areas, tide gates at the Ashley River and Cooper River to reduce the impacts of storm surge, and a levee system along the Ashley River to protect the East Central Peninsula.

Community pushback and Nature-based alternatives

After the USACE sea wall proposal was published for the public review, multiple debates emerged across the Charleston communities against the wall. The criticisms of the study included the environmental impacts concerns in respect to the local area, including damage to marine habitats and wildlife. (Chamberlain, 2020). The project could lead to erosion of nearby beaches and negatively impact the area's tourism industry. Community groups have raised the equity concerns as the project disproportionately impacted the low-income and minority populations. There was not enough community engagement throughout the planning process (Charleston City Paper, 2020). The experts questioned the method of the study, arguing that it did not fully account for the potential impacts of climate change and sea level rise, and relied too heavily on historical data. (Chamberlain, 2020; The State, 2020). Following the community's pushback, the study was updated and partially integrated green infrastructure solutions.

Alternative plans and civic efforts

There were several alternative perimeter protection strategies developed and proposed for the city. The comprehensive plan (City of Charleston, 2021) accommodates the USACE proposal while adds the soft measures of protection such as downzoning, ecosystem preservation, and elevation-based zoning. The alternative strategies of Coastal Conservation League (2019) and Charleston Civic Center Design Division (2021) prioritized nature-based and hybrid solutions for flood protection, such as wetlands and building living shorelines, instead of solely relying on traditional hard infrastructure. This approach provided flood protection and offers additional benefits such as improving water quality and enhancing habitat for wildlife. Biohabitats and One Architecture have proposed a flood protection vision for the Charleston Peninsula focused on ecological restoration and resilient design. Proposed perimeter strategies included oyster reefs, "blue-green" corridors for wildlife, stormwater infiltration, and flood protection, parks and rain gardens, wetlands restoration, and horizontal vegetated levees. The alternatives emphasized the importance of community engagement in the design and implementation of these strategies.

I referred to the visionary concept developed by Biohabitats Inc. and One Architecture and Urbanism – “Imagine the wall” in terms of ecosystem-based solutions, perimeter cross-sections, and model areas. I also used the latest science in NbS to determine the suitability of their allocation based on the NNBF international manual prepared by USACE (Bridges et al., 2022). Following the vision of “Imagine the Wall”, I based the solutions of my model on the shoreline ecosystems naturally present in the area. Wetlands, salt marshes, and sandy dunes are predominantly shaping the natural shoreline morphology of South Carolina generally and the area of interest (AOI) specifically.

Data variables and sources

Departure point

I took an economic development vista on the coastal nature-based adaptation strategies to assess the benefits of adaptation in terms of operation loss prevention for the tourist and retail sectors of the economy. My focus on the indirect benefits of NbS as factors of economic growth is based on the goal of defining business output dynamics that these perimeter solutions are accounting for. I chose a city scale for this assessment as it is associated with implementation of the landscape and ecosystem solutions (Hein et al., 2006; Raymond et al., 2017). This scale also helps define local economic effects and potential factors attracting local investment sources on the further steps. The rapid assessment model is aimed to support local governments in estimating the effects of adaptation strategies for economic activity. Therefore, it omits detailed physical damage and construction cost assessment falling beyond its objectives.

Data

Data slices

My approach combined several methods and respective primary and secondary data slices. It is flexible to update it with the newer risks and socio-economic development data as it evolves. The analysis involves four major data slices with the respective variables as shown in the Table 05:

- Flood impact assessment of the units against major flood hazards defined probabilistically on the local scale with the induced operation disruption;
- Adaptation strategy location, spatial characteristics, and flood exposure reduction associated with its performance

- Economic benefits of risk reduction – estimated monetary values of the extent to which NbS allows the reduction of the hazard damages to the tourism sector.
- Recreation co-benefits - impacts for the local economy in terms of recreation activity and related visitor spendings based on the new green space and area attractiveness;
- Scenarios for planning – adaptation pathways defined by the land use trends and flood risks for the short-term and long-term time horizons.

Table 05. Simplified structure of the research strands, methods, inputs, and related uncertainties

	Model strand	Approach	Inputs	Source	Uncertainty and compounding errors
1	**Flood impact assessment**	Basemap	Administrative subdivision, roads, water bodies	TIGER, Census.gov	Do not match with the shoreline configuration completely
			Shoreline configuration	CUSP	Changing configuration as a result of geophysical processes
			GIS services location by HAZUS	NSI	Changing development patterns
			Topobathymetric DEM	NOAA Digital Coast	Changing sediment patterns
			Current and future zoning	Charleston GIS services	Lack of certainty on the future land-use implementation
			Historic places and tourism overlays	Charleston GIS services	Averaged values, might need comparing with the local studies
		Flood impact assessment	GIS model of flood risk simulation for the planning horizons	USACE, 2022	Scientific uncertainties on climate change projections
			Sea level rise projections	Climate Central, Kopp et al., 2017	The probabilities of occurrence are not defined
			Business locations by occupation class	National structure inventory, NSI	Changing development patterns
			Depth Damage Function (DDF) curves from the BCA methodology	FEMA, 2009	Averaged values, might need comparing with the empirical studies

			Service interruption multipliers assigned by sector	FEMA, HAZUS	Averaged values, might need comparing with the local studies
			Output per building for the retail/tourist sector aggregated on the block level	BEA, BLS, 2022	Multiplier tables are generated by BEA. User cannot modify industry production functions
2	**Adaptation strategy**	Geocoding the alternative strategy	GIS model of NbS solutions by a coastline sector	Biohabitats, Inc. & One Architecture, 2020	The design stage of project – probably lacking parts of the attribute data
		Local conditions for the NbS suitability	Sediment transport patterns	The Nature Conservancy, 2021	
				Berman et al., 2007	Might be too generic as analyzed for Virginia
			Design considerations	Waggonner & Ball, 2019	Recommendations for two segments of the coastline
				CCL & Sherwood Associates, 2021	Recommendations for two segments of the coastline
				Civic Design Center, 2021	Compilation of several projects – though might be complementary
3	**Economic benefits of risk reduction**	Benefits of operation loss prevention	Design considerations and properties	Bridges et al., 2022, Keenan et al., 2016	Needs more observation-based data
			Adaptation capacity	The Nature Conservancy, 2021	Needs more observation-based data
		Alternative - benefits of op. loss prevention	NbS attributes by the coastline type - vegetation robustness, flood attenuation	Bridges et al., 2022, Arkema et al., 2013	Might be generic and need more observation-based data
4	**Co-benefits Recreation activity**	Tourism attractiveness	Annual tourist and recreation attainment	The College of Charleston	Might be aggregated data, otherwise detailed surveys needed on the further stages of research
			Revenues localized and correlated with the activity in coastal area	the Office of Tourism	
			NbS area, visitors capacity, and attractiveness weighted by sector, considering seasonality	Biohabitats, Inc. & One Architecture, 2020	
5	**Scenario-based planning**	Adaptive pathways method	-	de Ruig et al., 2019	

			-	Aerts et al., 2018	
			Economic development scenarios affecting intensity of the services located in the coastal zone	Charleston GIS services	Needs to be aligned with the economic development strategies

Variables and units of analysis

The key variables involved in my model`s research strands are shown in Figure 05. They include protection level measured in prevented business operation loss of the retail and tourist sectors, and the potential of the revenue flows generated by creating a new recreational area. I estimate the ecosystem services quantitatively in the annual economic output per sector. Independent variables include coastline topo bathymetry, flood depths and probabilities, services location and elevation, depth damage and business interruption functions, land use trends, wetlands allocation, sediment patterns, walkability index, and public spaces for tourist and recreational activity.

To assess those parameters, I established the relevant units of analysis. The NbS solutions are assigned to the shoreline by the suitability class. I define the ecosystem-based adaptation suitability based on terrain, depth, storm observations and directions, habitats location, navigation routes, and land uses. I am identifying the optimal perimeter protection strategy by a ranked segment as a cross-section, or a transect, with the attributes of height, length, and robustness. The output of the ecosystem-based solutions allocation suitability is the shoreline sectors with correlating parameters matching the array of solutions: saltwater marsh and wetland restoration, horizontal levee, green parkway, living breakwater and barrier islands, protective bulkhead with riprap (Bridges et al., 2022, Keenan et al., 2016)

Furthermore, I focused on the local scale assessment with the focus on specific economic sectors, therefore I choose buildings as a point feature class to assess the risks and benefits. National Structures Inventory provides physical and economic attributes per an occupation class and building type, while the polygon feature class of building footprints is used to visualize the results. The discrepancies between the point feature class and the building polygon centroids will be fixed utilizing the ArcGIS and Grasshopper spatial join tools. Finally, I aggregate the results by a model area defined as a district with similar land use patterns along the coast.

Data sources

I used mostly open data sources, aiming to build a framework accessible for the local authorities and municipal planners as a first estimation. I will access geodata for laying out the GIS model of ecosystem-based adaptation strategy from Esri, Census data, open-source sea level rise projections and hazard records (Climate central, Kopp et al., 2017; FEMA, NOAA, HAZUS MH model). Also, I build this assessment upon the secondary data collected from the research papers on the city of Charleston flood protection, USACE Peninsula Coastal Flood Risk Management Study (USACE, 2021), and alternative proposals for the Peninsula, including Dutch Dialogues (Waggonner & Ball, 2019), Imagine the Wall (Biohabitats, Inc. & One Architecture, 2020), Beyond the Wall (CCL & Sherwood Associates, 2021), and Charleston Peninsula 3x3x3 (Civic Design Center, 2021).

For the economic model I need services allocation and output features obtained from Hazus datasets and local tourist agencies. I also obtain block-level and parcel-level data on demographics and economic activity from these sources and from census tabular data. The College of Charleston and the Office of Tourism annual reports are the sources of data on tourism economic impact and annual revenues with the annual trends (The Office of Tourism Analysis, 2017; Charleston Chapter of Commerce, 2022).

Spatially explicit model: GIS and Grasshopper interface

GIS and Grasshopper played central roles in constructing the model algorithm and conduct the assessment. An area of interest – Charleston Peninsula – in the local scale is a reference between GIS project and Rhino-Grasshopper parametric interface. While I used ArcGIS to collect and prepare data slices, Grasshopper allowed to analyze it modular generative algorithm. I ran the geographically explicit and economic strands of assessment sequentially in Rhino with the Grasshopper to allow the recurrent model refinement. Grasshopper algorithmic modeling has multiple benefits over the ArcGIS tool of Model Builder in terms of flexibility, ease of adjustment, and functional capacities for complex models. The outcomes of the model are parameters per model area convenient for further adjusting a solution configuration.

ArcGIS project

The GIS interface is an essential model tool to collect, prepare, and aggregate all data layers. They were collected from open sources using the local projected coordinate system of Universal Transverse Mercator WGS 84/UTM zone 17N (code 32617) corresponding with South Carolina EPSG:4326 - WGS 84 (World Geodetic System 1984 ensemble) here used to establish the correct geosystem correlation between two interfaces I used. GIS data shapefiles exported from the ArcGIS framework to Grasshopper included environmental and land use context, coastline segments for adaptation strategy, census blocks, model areas, business inventory, building footprints, and high resolution topobathymetry rasters.

Grasshopper and Rhinoceros

I combined ArcGIS project and Grasshopper model to unleash parametric modeling opportunities. My goal was to lay out a scenario-based framework illustrated with the climate and socio-economic scenarios and establish a tool for estimating the co-benefits provided by the NbS. Data preparation steps were still required with the ArcGIS, as the precise tools for joining and aggregating numeric attributes by geolocation are easier accessible in the geoinformation analysis tools. Also, this step fixed the discrepancies in the attributes.

Grasshopper and Rhino provide the convenience of transition from site analysis to design development stages. I developed algorithms for the economic assessment in Grasshopper to build an intuitive visual programming interface. All GIS and tabular data processed as a Grasshopper model and visualized in Rhinoceros provide an accessible framework for the further stages of design. The connection between two interfaces works through exporting ArcGIS feature classes to Esri shapefiles. Further, using plugins Heron and Bison the data is laid out and to the algorithmic operations to compose output geometry with the scripts. An algorithmic approach enabled the rapid generation of alternatives to transform into Rhino 3d geometry. Using spatial and 3D interface for geographic and economic analysis in this model I aimed to make a step towards better integration of the latest observation- and science-based knowledge with the practical outcome-oriented design development. The resulting model and its framework is yet a concept, though the script has the potential to become a decision support tool.

Part 1. Environmental resilience. Risk assessment and NbS suitability

Conceptual basis of the method

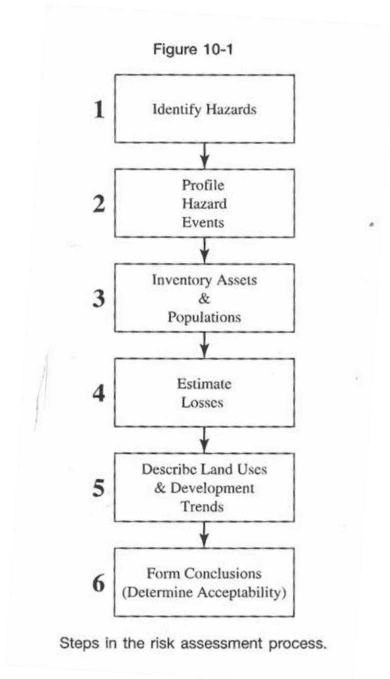


Figure 03. Risk assessment framework (Schwab et al., 364)

Assessing risks for the assets and ecosystem

I considered SLR and storm surge risks in the moderate and high emission scenarios - RCPs 4.5 and 8.5. A comprehensive hazard assessment was beyond my research goals, therefore I decomposed the existing methods to use partially in my research strands. Following the method of Schwab et al (see Figure 03), I determined flood hazard risks for the area of interest, then assessed its geographic extent, magnitude, duration, frequency, and probability based on the latest data and historical records from the local tidal gauge (Charleston water level station, ID: 8665530). Furthermore, I examined the vulnerability of my units of interest - tourism and recreation services in the area - to these hazards and their relation to unaffected services and to the Modeling areas. Using estimated HAZUS values of the daily economic output per occupation class, I assessed potential losses under chosen scenarios. Finally, I analyzed the conditions suitable for allocation of adaptation solutions. In this step I focused on the natural and human-made conditions needed for the living shorelines rather than the complete economic and social need in this shield as previous studies mostly did.

Multiple Flood Models

My model needed to simplify flood risk probabilities to unite them within one framework. Thus, I estimated the risks of flooding using the latest and most likely to occur Sea level rise projections together with the probabilities of coastal storm surge. I aimed to incorporate latest knowledge on the contributing factors of sea level rise and define the units to measure the risk. For my assessment I needed to identify the time dimension - days of the flood levels preventing business from operations and visitors from travelling and spending on the recreation and tourism services. Determining the latest SLR projections I based the risk assessment on the comprehensive research of Kopp et al (2017) as it considers all the currently known contributing factors. I incorporated Climate Central data on the storm surge levels and probabilities according to this study, although their discrepancy with the USACE Peninsula study is worth mentioning. projection as Peninsula study due to cohesion and data availability issues (USACE, 2022). More information on the choice of climate scenarios and flood risk levels is provided in Appendix 01 (pp. 114 - 118).

Ecosystem-based adaptation as an emerging approach

International NbS guidelines

In my model I based the ecosystem performance on the latest aggregated international effort conducted by USACE – NNBF (Bridges et al., 2022). The main NbS flood risk mitigation attributes are discussed in the Appendix 02 (pp. 118 - 125). However, in further performance assessment or Flood Risk Mitigation benefits of the wetlands, dunes, and barrier islands, the guidelines suggest using the empirical formulae and numerical modeling (USACE, 2002; FEMA; 2005, 2016; CIRIA, CUR, and CETMEF, 2007; Barnard et al., 2014; and Resio and Westerink, 2008).

Units of assessment and model assumptions

In my model I take two main units of analysis - shoreline perimeter and building footprints which conceptually stay constant through the scenarios at hand. As such in each research strand I aim to represent both environmental and economic vistas and their relationships with the available data. The third unit which allows assessing the protection levels is the shoreline profiles (cross-sections) representing attenuation capacities with the parameters of robustness, height and length. The major determining factors for risk assessment and NbS suitability are changing flood depths and sediment patterns, zoning, assets density and values, and habitat observed location. I had to take an assumption that the patterns I based suitability assessment on will sustain constant for the purposes of this research and the lack of scientific data on local habitat patterns and conditions. Nevertheless, coastal marsh migration and coastal squeeze processes and impacts on the ecosystem and nature-based solutions need to be explored in the further stages of this model development (NOAA sea level rise viewer, 2022)

Scenario-based planning

Finally, the framework of my model involved adaptability as an essential tool of coastal management in uncertain conditions. This approach allowed the model to assess economic dynamics over time of implementation and maintenance of the ecosystem-based solutions. The common practice of economic assessment might lack the flexibility of solution depending on progressing scenarios, which represents a significant limitation in the face of uncertain climate conditions and constantly changing socioeconomic context not always following the strategic goals. The method I use for this step is referred to as “Adaptive pathways” (Aerts et al., 2018; de Ruig et al., 2019). Considering the risks and adaptation under several scenarios it informed decisions via correlation of risks and benefits over time and highlighting points of transition to another approach over time.

For instance, under high-risk scenarios, the ecosystem-based solutions will show insufficiency. Then additional hard infrastructural solutions might be implied to prevent the urgent risks, and some more drastic levels of exposure (higher number of days of the storm surge and continuous tidal floods) will result in infeasibility of all adaptation measures and then suggest retreat or relocation for the respective services from that area. The first part of the model is focused on the assessment of the natural underlying factors of coastal protection. Thus it is laying out a number of scripts for 10 and 50- years flood and storm projections based on the latest science with the opportunity to append the updates. Then, the second part allows to inform those pathways for various business sectors, thus providing the general recommendations for a resilient balance between economic and environmental benefits. (Aerts et al., 2018)

The Adaptation pathways

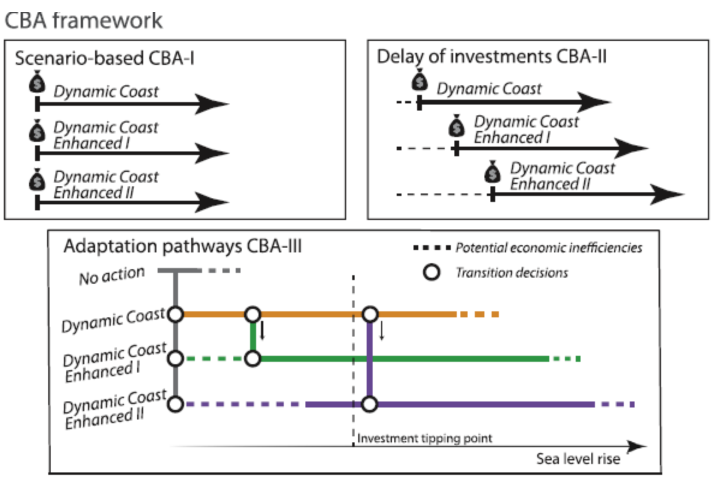


Figure 04. Schematic Figure of Adaptation pathways, Aerts et al, 2018, de Ruig et al., 2019

The adaptive approach of Aerts et al (2018) used relative projections for flexible adaptation based on estimated costs and effects (see Figure 04). An adaptation pathway is defined as the collection of measures to lower the risk, while the combination of pathways allow the transition from one scenario to another over time controlled by an array of uncertainties in SLR projections and natural dynamics. This potentially spreads the costs and allows the choice of the ratio of nature-based to engineering options such as levees and sluices. (Aerts et al., 2018)

The two timespans chosen for the assessment are 2032 and 2082 cohesive with the USACE's Charleston study time horizons. I consider two main emission scenarios to inform potential choice of a solution in future - the RCP 4.5 and 8.5, and the levels from NAVD88. Development growth indices correlate with the tourism economy forecasts (SCBEA, 2021).

According to South Carolina BEA projections, the sector of tourism is expected to grow by 10 % annually after the year 2023. I considered this rate for the moderate risk scenario, whether the extreme, or business as usual, emission scenario would force the gradual decline in activity due to the limited seasonal opportunities for the business operations. These rates were set based on historical data on the Economic Output of recreation sector, evolution of economic growth, and the World Bank and PwC Economic projections (Charleston Metro Chamber of Commerce, 2022). These parameters correlated with the land use dynamics are shown in the Table 06.

Table 06. The model SLR Scenarios (Kopp et al, 2017, Climate Central, 2023)

	Scenario 1 short-term medium (10, 4.5)	Scenario 2 medium-term medium (50, 4.5)	Scenario 3 short-term high (10, 8.5)	Scenario 4 short-term medium (50, 8.5)
SLR	1.3 ft	4.2 ft	1.3 ft	5.8 ft
SLR + Storm Surge (1% AOP)	5.2 ft	8.1 ft	5.2 ft	9.7 ft
Development growth	20%	20%	10%	1%

Two emission scenarios and two time frames of relative SLR and respective storm probabilities were combined with the expected dynamics of economic development. Adaptive pathways approach helped assessing dynamics over time of implementation. As an example, it is not likely that during the next decade global emission patterns will change from Business-as-usual to moderate emission (RCP 4.5). Decision-makers might prefer following a scenario for the higher flood risks in the short-term. This allows them to inform businesses of risk and accomplish emergency preparation instead of hard adaptation. But, as we reach the line of 2032, the long-term scenario can change to Moderate projections with the correlated SLR projections and reduction of businesses at risk – in case considerable improvements in climate policies and emission reduction will be achieved globally. The project implemented then will start paying off in terms of broader protection of tourist services and potential improvement of recreation qualities of the areas of downzoning and retreat.

Strand 1. Hazard risk and exposure

Shoreline and topobathymetric configuration

Working on the first model module, I made an assumption that the shoreline configuration will be stable in the timeframes of this research. The graphic representation of the shoreline is obtained from National Shoreline Data Explorer by NOAA Continually Updated Shoreline Product (geodesy.noaa.gov/CUSP) CUSP aims to deliver a continuous shoreline with frequent updates to accurately represent changes to the land-water interface based on the data from at least 15 federal agencies, numerous state and local organizations along the coast, as well as academic institutions and private companies. CUSP incorporates shoreline and alongshore features - groins, breakwaters, and jetties.

The geomorphology of the Area of interest played a critical role in the further assessment as it informs the shoreline and buildings exposure levels. Moreover, we need the seabed slopes steepness in defining the areas suitability for wetlands, salt marshes, and barrier islands. Using both DEM and Bathymetry is essential to explain the structure of the shoreline as a function of a continuous terrain. Most of the raster terrain data available only includes either above water or underwater levels. The USGS 3DEP LidarExplorer provides a choice of LiDAR and DEM files. The data on the surface topography would not be sufficient as the goal is to analyze the relief of the AOI as a seamless database. Therefore, for the purpose of my study the best possible source would be the seamless digital elevation model obtained from the National Center for Environmental Information Bathymetric data tiles (https://www.ncei.noaa.gov/products/coastal-elevation-models).

Physical assets

I determined the area of interest similarly to USACE study based on the census tract of Charleston City Center. All the data aggregated in ArcGIS is extracted for this area in the interest of model operation. My major units of assessment – retail and tourism businesses by the building footprints and model areas - are prepared in ArcGIS based on the inputs listed in the data sources (reference). I spatially assign the NSI point feature class with occupation types of lodging (RES4), Retail (COM1), and entertainment (COM8) to the building footprints to have the better spatial distribution of the services. Model areas are the units of NbS assessment, and therefore should be tailored to one specific adaptation solution. USACE Peninsula study (see Figure 05) and Imagine the Wall study (see Figure 06) had different model areas subdivision. Since urban patterns inevitably define the potential for various perimeter solutions, the land use patterns identified the areas of this model assessment.

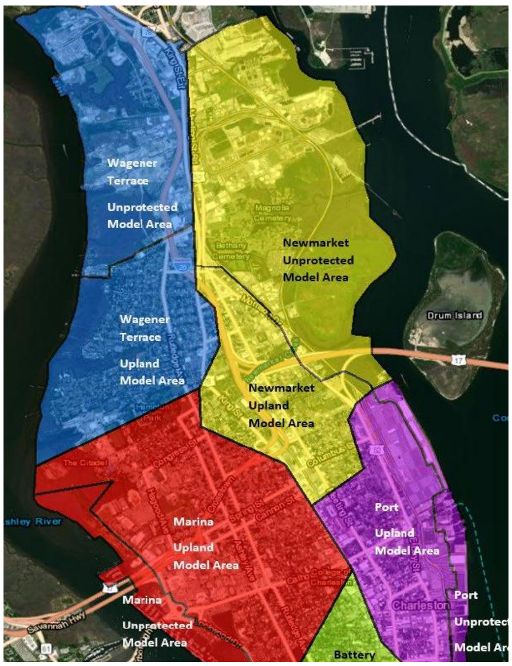


Figure 05. USACE, 2021. Charleston Peninsula Study Model Areas

Figure 06. Biohabitats inc., One Architecture and Urbanism. Imagine the wall, Perimeter Strategies

Business occupation types and other NSI attributes are spatially joined to the services within the area of interest per a building footprint. ArcGIS project allows to fix the buildings data discrepancies and join the economic parameters per occupation type from the HAZUS databases. Further, I build the Services module in Grasshopper to spatially analyze the services at hand in relation to the projected water levels. Having the footprint centroids projected to the DEM in Grasshopper, I computed their elevations to further identify the flood risk exposure in terms of damage levels causing temporary operation loss using the Hazus definitions for COM1, COM8, and RES4 occupancy classes.

Flood risk projections

I used NOAA flood mapper SLR raster datasets for the visual representation of the risk levels in ArcGIS project . The more precise flood levels per scenario are defined earlier in "Scenario-based planning" and further used with the Flood Impact module for the water level simulation in Grasshopper Adaptation scenarios. Each of the four scenarios correlated with a building threshold elevation for the operation disruption. This threshold is generally estimated as 2 ft below a water level according to the HAZUS flood module for the given occupation classes. This means that in Adaptation scenarios 1 and 3 all businesses of interest located below -0.7 ft were considered completely closed, and below 3.2 – temporarily disrupted under storm surge. This occurrence will happen once a decade considering acceleration of the storms (Kopp et al, 2017, Climate Central, 2023). The threshold levels are shown in Figure 07.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
SLR	-0.7 ft	2.2 ft	-0.7 ft	3.8 ft
SLR + Storm Surge	3.2 ft	6.1 ft	3.2 ft	7.7 ft

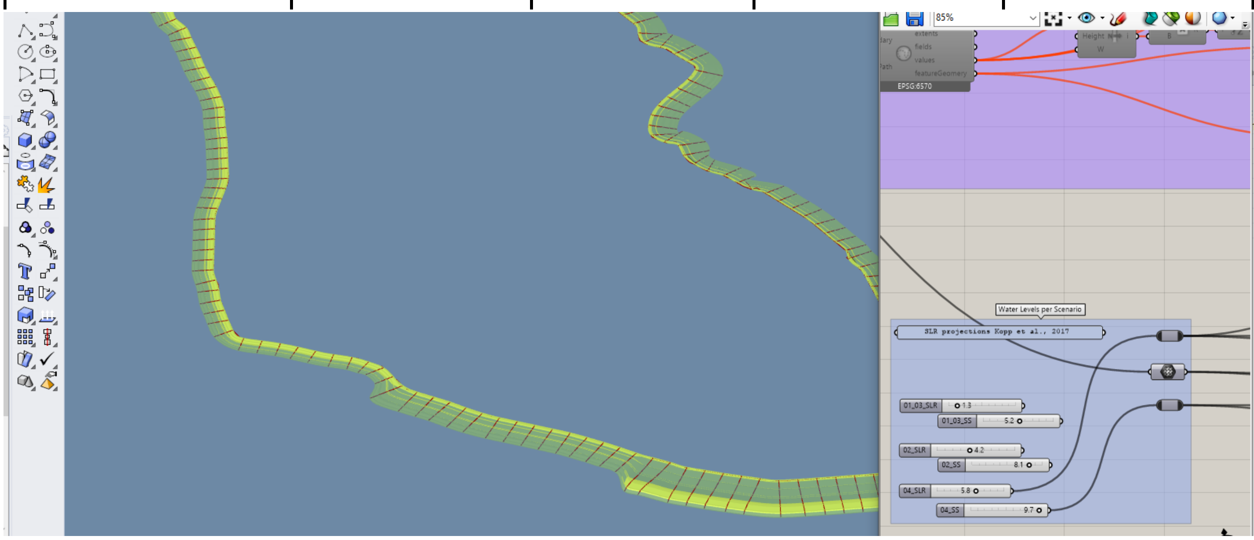
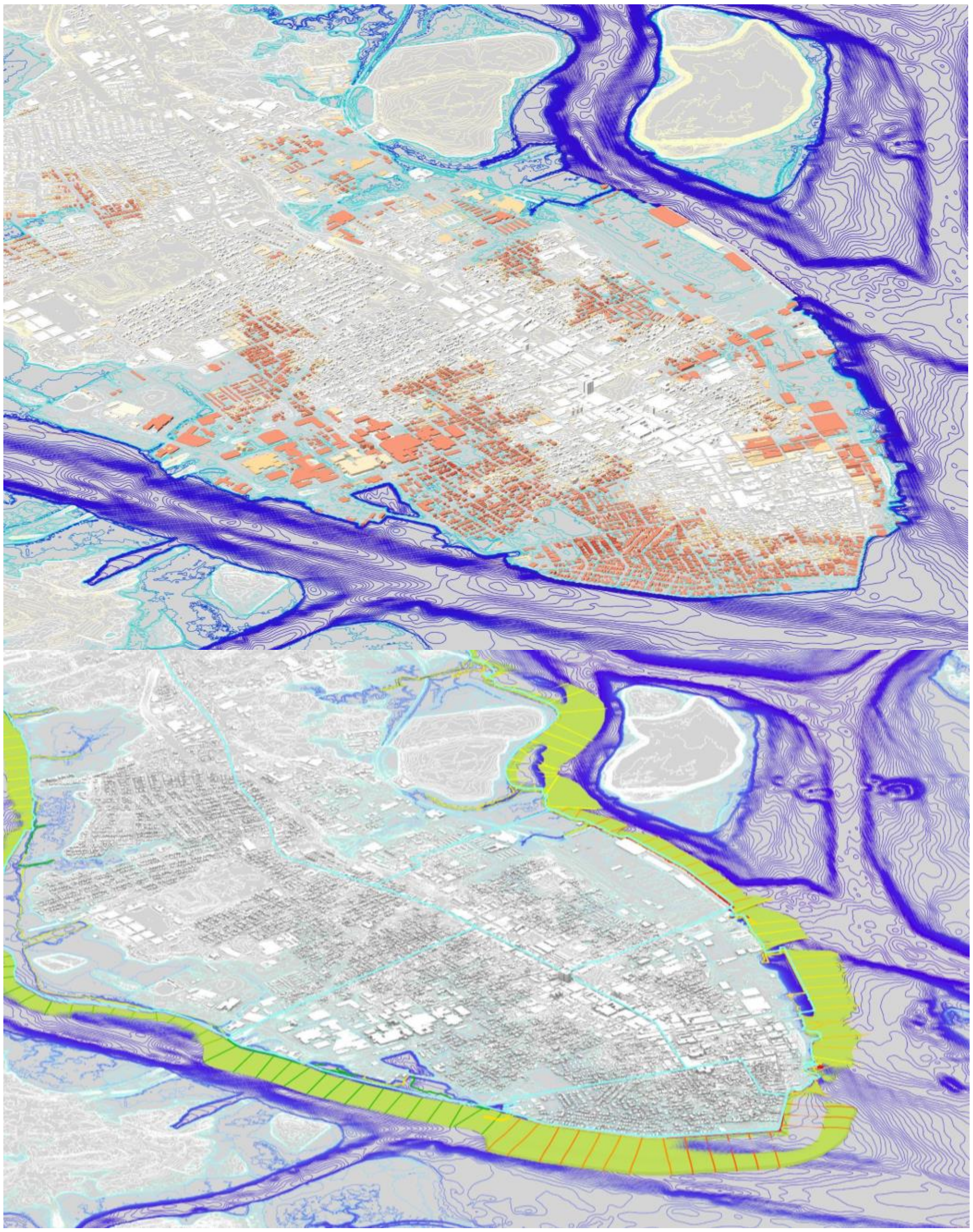


Figure 07. Model Disruption levels Scenarios (Kopp et al, 2017, Climate Central, 2023). Application in Grasshopper algorithm

For higher accuracy of the disruption distribution, I needed to run the HAZUS Flood Risk assessment module. The model corresponds with a high simulation complexity and lack of transparency in computational methods. Therefore, I used the aggregated sector-specific data and damage function equations for this research strand consequently integrating the equation to the Grasshopper Flood risk module. The simplified flood risks considered for the two time-horizons are the SLR and coastal storm surge for the two climate change scenarios, as the highest probability of occurrence and highest severity respectively. Using the Model areas polygons I further aggregated the flood risks for the tourist sector in the areas of comparison as well as their relation to the unaffected establishments within the areas as shown in Figures 08-09.



Figures 08-09. Flood risk exposure under the 2032 scenarios with and without adaptation perimeter

Strand 2. Adaptation strategy - the NbS configuration

To allocate the NbS solutions for the lifetime of the project I needed to build the algorithm assigning specific solutions depending on the shoreline and adjacent conditions. Based on the NNBF guidelines (Bridges et al., 2021b), the main factors to consider are land use and land cover, current structure of a shoreline, hydrological conditions, topography and slope of the site, ecosystem type, and the sediment trends. Sediment transport patterns and coastal geomorphology allowed the long-term projections of the shoreline dynamics based on the historic records. The respective size and robustness of a solution need to be determined based on the depth of a projected water level. Cumulatively, these parameters determine the attenuation capacity of a shoreline solution. The inputs to assessing their performance in this model are the attenuation capacity per an NbS cross-sections.

Defining suitability

The suitability ranking was performed in ArcGIS with Spatial Analyst tools. The featured suitability parameters were used as secondary GIS data: Shoreline perimeter structure, Topobathymetry slope, Wetland types, Shoreline transformation index, Exposure to the maximum fetch energies, and Zoning patterns. Each of the parameters are ranked from one to five - representing the values gradient from the least suitable to the most suitable for the NbS sitting. The resulting NbS suitability ranking is calculated as an average value of the six variables and is shown in the Figure 16. These parameters might be updated in ArcGIS equation based on the local conditions and should be further defined based on the updated research. I explained their components per suitability factor in detail in Appendix 02 (pp. 118 - 125)

Figure 10. Resulting shoreline suitability ranking based on the Module 2 "Adaptation strategy"

Strategies and their protective capacity

As was discussed in the Conceptualization chapter, I base my NbS performance capacity modeling on the NNBF guidelines data for the different solutions per a profile. Our five protection types are assigned the following parameters. The ranks of adaptation perimeter`s robustness/ height parameters define the percent of their attenuation capacities for various water levels. Thus, I assessed the levels of mitigated flood risks per a transect. Parameters of height and length of the solution were defined by design. The parameters of vegetation attenuative capacity were harder to define due to the lack of observations. The ongoing research in ecosystem-based adaptation showed that the surge-attenuation rates as defined by a wetland size; typically, are 1.7 to 25 cm/km (Leonardi et al. 2018).

The NbS configuration and performance

I initially used the CUSP shoreline feature class to rank the segments by the NbS suitability. The profiles are assigned to the shoreline curve and lofted into one smooth continuous mesh-shape in Grasshopper using the ranks as the keys. Ranking the shoreline segments on the scale from one to five – least suitable to the most suitable –informed the choice of a Nature based solution in a simplified manner as a classification by a key in Grasshopper algorithm. The list of keys for the choice of a solution are defined based on the NNBF guidelines and the coastal resilience toolkit developed by SCAPE and One Architecture and Urbanism. This secondary data slice was enriched with the attributes of robustness, attenuation, length, and area defining flood protection capacity. Then I modeled the prevented flood risks using the elevation and exposure layer estimating the extent of protection with the records-based probabilities. The choice of solutions accomplished with the suitability module generated an adaptive coastal perimeter. Using shoreline polylines ranked by suitability and simplified by model areas boundaries, I assigned the perimeter solutions transects along the shoreline.

SLR protection

The ecosystem-based solutions have comparable shoreline flood protection capacity to that from hard infrastructure. Important parameters to consider for both are the height of crest and width of basement, which shall be aligned with the levels of MHHW and sufficient for the ecosystems to adapt and adjust.

Living shorelines differ from engineered solutions in many ways, particularly in their dynamic of interaction with fluctuating water levels. Vegetation density and height characteristics help to attenuate wave heights and disseminate them in a sponge manner. At the same time, the wetlands, seagrass, and other vegetation are not capable of permanently reducing water levels. In this model I have examined the NbS interaction with SLR and coastal storm surge. The required level of SLR reduction for an area of interest should be performed adjusting physical characteristics of an NbS cross-section and its structural, relatively "hard" base. Storm waves mitigation is more complex and depends on many factors. Nevertheless, when examining the ecosystem capacity to reduce them I operated with both parameters of ecosystem "core" location and vegetation robustness, density, and height.

In modeling and estimating flood mitigation benefits I needed to formulate my assumptions clearly. As the model works on the city scale with respective levels of approximation, flood mitigation capacities of vegetation parts will be expressed by exposure reduction indices based on the latest research and case-studies discussed in literature review . Each of the four model scenarios consider two levels of water for projected sea level rise and expected extreme storm waves of 1% annual probability of occurrence. Thus, a "without project" scenario set two variables of flood exposure – permanent SLR and temporary Storm surge.

In this model I applied the approach of Barbier et al, 2013 assessing the efficiency of flood protection of a perimeter solution using the attributes of perimeter transects. At this level of abstraction I simplified the adaptation transects based on their interaction with floods and waves. The structural core of these interventions ("Core") and the soft, living ecosystem layer ("Sponge") are assumed to perform optimally against the SLR and coastal storm surge respectively. According to the latest international studies, the recommended geometry of the Core and observed performance of the Sponge are shown in Table 07:

Key	Nature based perimeter solutions	Height	Width	Slope	Vegetation height	Percent Surge Reduction	Reference
1	**Barrier Island**	7 - 10 ft	100-1000 ft	3-20 %	1 - 10 ft	up to 90%	CRPA, 2023, Bridges et al., 2021b
2	**Living bulkhead/ riprap/ ecoshape**	3 - 12 ft	50-100 ft	10-30%	1 - 2 ft	50%	SCAPE ecoshape 2020, VIMS, 2023
3	**Dikes and levees with revetment /oyster tecture**	6 - 15 ft	50-100 ft	10 - 30%	1 - 5 ft	70%	USACE, 2022, AECOM, 2018, CRPA, 2023
4	**Horizontal levee**	6 - 10 ft	250 - 500 ft	3-5%	2 - 20 ft	90%	Currin et al., 2019
5	**Wetlands restoration**	5-10 ft	500 - 1000	1-3%	2 - 5 ft	up to 80%	Temmerman et al., 2013, Bridges et al., 2021b

Table 07. Wave-attenuation attributes of NbS

In the interest of this model I omitted the indices of wave attenuation depending on the NbS location as related to the shore, as they are considered external factors of performance and are represented in a spatially explicit manner. The internal factors of flood reduction stated that the amount of waves reduction depends on the vegetation density, robustness, and area below the water. The modelled perimeter protection is shown in the Figure 11.

Figure 11. Living shorelines perimeter generated with the "Adaptation strategy" module

To estimate the reduction of flood levels provided by the NbS I used their research-based attenuation capacities as follows: Wave height*(1-Attenuation capacity per ecosystem solution) = Level of crest height overflow - in case the transect allowed the crest height with the additional threshold of 2 ft over the projected SLR. Independently from the resulting height of the construction, the elevation points of buildings exposed to the risks of disruption due to the waves passing through the vegetation is expected to reach "Wave height*(1-Attenuation capacity per ecosystem solution) +SLR - 2ft . These levels vary per each of the planning scenarios and transect crest heights. Generally, most scenarios allow the height of 5-6 ft over the current sea level, but the model shows local-specific limitations in this parameter. The Table 08 shows thresholds per a of living shoreline type. More details on the NbS performance are discussed in the Appendix 03 (pp. 125 – 134)

Model Areas	NbPS Key	NbPS type	Wave attenuation	Disruption elevation, Sc1-3	Disruption elevation, Sc2	Disruption elevation, Sc4
1 - NOMO/ East Central	**3**	Dikes and levees with oyster tecture	0.7	2.47	**5.37**	**6.97**
2 - Wraggborough/ Port	**2**	Living bulkheads with ripraps	0.5	3.25	**6.15**	**7.75**
3 - East Bay	**3**	Dikes and levees with oyster tecture	0.7	2.47	**5.37**	**6.97**
4 - Battery/ civic center	**1**	Barrier Island	0.9	1.69	**4.59**	**6.19**
5 - Harleston village/ Marina	**5**	Wetlands restoration	0.8	2.08	**4.98**	**6.58**
6 - Wagener Terrace	**4**	Horizontal levee	0.9	1.69	**4.59**	**6.19**

Table 08. NbS suitable for the model areas with the estimated levels of waves exposure

Part 2. Economic resilience. Co-benefits of nature-based adaptation

Conventional approach to evaluate the benefits of adaptation strategies

Traditionally, economic impact assessment associated with the adaptation solutions involves the extent a solution reduces direct damages expressed in the physical and operation loss induced by specific hazard frequencies on a specific area (Arkema et al.,2013; FEMA, 2009; Barbier et al., 2019). My study focuses on coastal recreation and tourism business activity. Thus, I combine the operation output loss prevention for the tourism and recreation services with the landscape metrics affecting recreation activity. Economic parameters are dynamically changing over time depending on the development and the industry trends.

Strand 3. Economic benefits of operation loss prevented

This strand of research estimates the extent to which generated NbS reduces the potential economic loss correlated with the risks of flooding for existing and projected state of the tourism sector. The key variable here is the cost of disruption and recovery in terms of the economic output per business unit. There are other factors to be considered such as the access to the services at hand, their attractiveness and land use trends. The risks associated with coastal development arise from the intensive uses, hard perimeter infrastructure, and insufficient building setbacks preventing the ecosystems to develop adaptive capacity. Existing urbanization risks were assessed by the land use type and hard perimeter infrastructure, with the respective assigned ranks on the scale from 1 to 5 - from the least to the most desirable for ecosystems. Future urbanization-induced risks will take more in-depth analysis of trends in zoning and demographics which are beyond the scope of this study.

There are several ways to estimate the rank of business output loss, or intangible damages. In the last strand I assessed the average number of days without operation based on the probabilities of water levels exceeding a mark of 2 feet above a building basement per each of scenarios and recovery time. Assessing the adaptive capacities of proposed NbS I compare these numbers depending on the reduced disruption time due to the floods. The economic values are determined based on the HAZUS multipliers per an occupation type, multiplied by the ranks of additional factors of attraction listed above. I then compared the outcomes by a shoreline model area to define the correlation between adaptation solution and the benefits provided.

For the goals of this research, I took an assumption that zoning proposed by the latest Charleston comprehensive plan will be implemented by the established long-term time horizon (2082) with the related increase or decrease in the risk rank and preservation or exit of the businesses. I processed this transition with the respective classification of the shoreline segments in ArcGIS (see Figure 12)

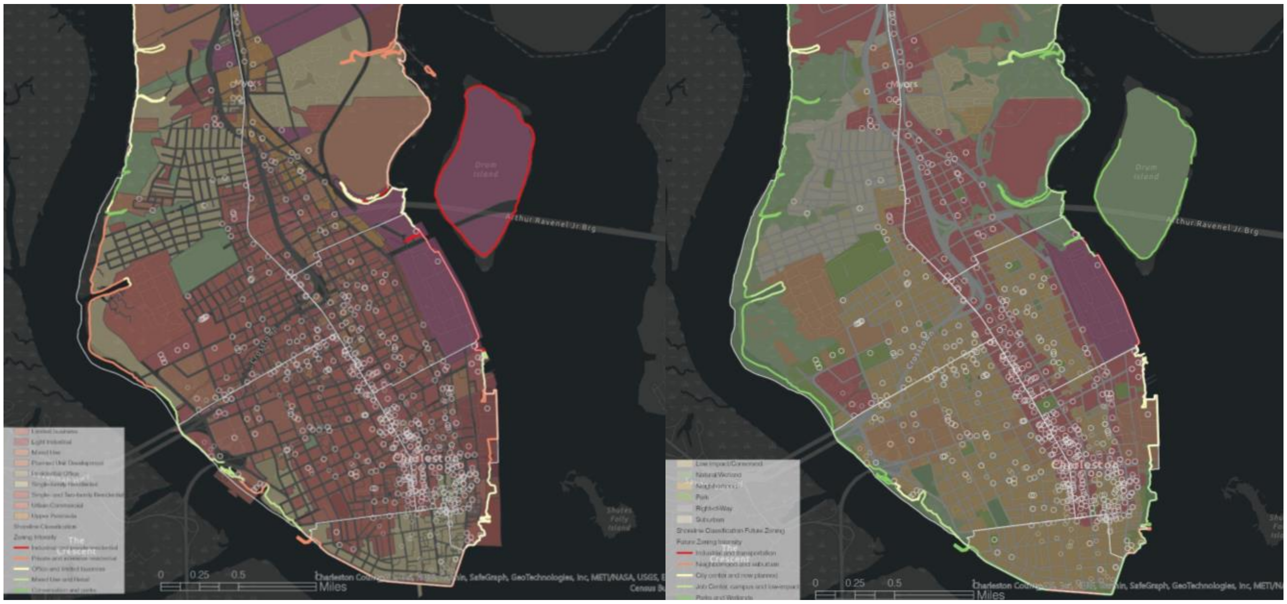


Figure 12. Zoning dynamics and NbS suitability/performance

<u>*Prevented loss of operation disruption*</u>

In the previous strand determined the businesses prone to complete and temporary disruption under various scenarios. The output parameter here is the industry output - total value of goods and services provided by industries related to recreation. I needed to define the costs of these risks comparing to the costs prevented by adaptation scenarios. I modified the FEMA/ USACE conventional method of economic output loss evaluation – as a part of the HAZUS economic impact model - to estimate the benefits associated with prevention of the business interruption of retail services, tourism, and recreation assets. The databases of the HAZUS model provide the aggregated numbers per sector and building types, with the shortcoming of having to index these parameters based on the local parameters further. They include service interruption multipliers by sector for the operation loss from the estimated damage. This determines which business relocates, experience longer outages, or exits under extensive damage conditions. Output loss per building is derived from the FEMA standard values per industry.

Business activity generated several types of income, which is the essential parameter that sustains the vitality and operation. Income losses occur when building damage disrupts economic activity. It involves the income loss assessment based on duration of disruption and ability to recapture across industries. It will be higher for those who produce durable output and lower for those who produce perishables or spot products. Table 09 provides the set of recapture factors that I used with the hazard-specific equations to estimate the various types of income losses for the economic sectors used in the direct economic loss module for hazards (FEMA, 2022. HAZUS 6.0 inventory manual).

Occupancy_Class	Output daily per sqf	BIF	Recovery time, days	OFR
RES4	0.627	18%	60	0.2%
COM1	0.546	35%	90	0.2%
COM8	1.318	17%	180	0.2%

Table 09. Economic parameters per occupancy classes (FEMA, HAZUS, 2022)

The indirect economic loss module of the Hazus involved the duration of business operation disruption by incorporating an input of "business interruption factor" (BIF) into the indirect economic impact equation. It represents the proportion of direct economic losses that result in a temporary interruption of business operations, and was used to estimate duration of the business interruption and the resulting indirect economic impacts. For flood events, the Hazus values are controlled by different occupancy types and sectors, reflecting the degrees to which business operations are disrupted by flood damage. The resulting distribution of these risks is shown in Figure 13. Business operation module is discussed in Appendix 04 (pp. 134 - 138).

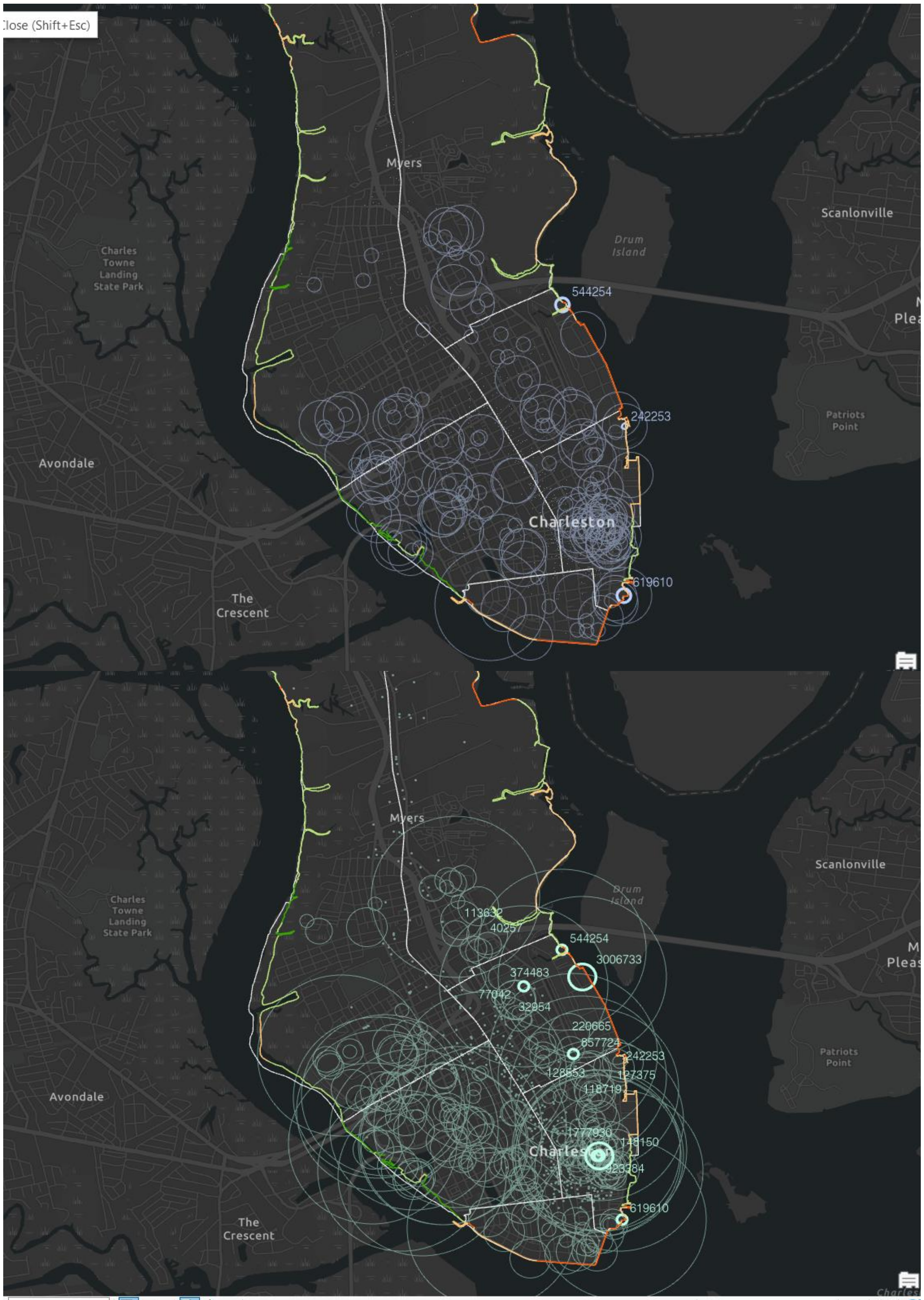


Figure 13. Economic risk distribution across the planning scenarios (FEMA, HAZUS, 2022) Economic benefits and residual losses for the long-term planning scenarios with the adaptive perimeter. RCP`s 4.5 (top) and 8.5 (bottom)

The first and second strands of my analysis allowed to identify the magnitudes of risk for the units of interest and assess their level of protection provided by the ecosystem-based solutions. The economic values of the risks and its reduction were measured by multiplying the establishments area in square foot per the HAZUS indices per the time of operation disruption. The multiplication of the standard values can leave out the local modulations due to the different levels of services external and local-specific factors discussed above. Then, we need to index the HAZUS occupation class numbers into the state-specific parameters using the NAICS codes. The sector economic growth projections are built upon the trends observed and extrapolated for the project timespan.

Weighing and extrapolating the values of ecosystem services

The output of the third strand of my analysis returns the values of economic output loss prevented by the adaptation solutions per a building aggregated by an economy sector and a model area. In measuring flood risk reduction benefits of the ecosystem-based solutions we need to choose the units of assessment the relation between a perimeter solution, businesses, and the local conditions. The most important and tailored to the takeaway scale is the impact per a model area which allows to directly compare the ecosystem type with the monetary values. For further in-depth research, we can also compare the results on the building scale to find the relationship via multiple regression or spatial autocorrelation models.

Each of the occupation types have additional external factors affecting the future economic development. Tourism and recreation develop based on accessibility and the infrastructure for the tourists to access facilities, as well as the attractions nearby (Office of Tourism, Charleston Chamber of Commerce, 2022). To assess the economic effects of NbS over time, I needed to connect network accessibility/ walkability models to flood risk mitigation to refine and project the value of ecosystem services across the scenarios. In that we first assess the access routes to the services at hand and then define how the adaptation strategies reduce the risks of their disruption. Second, I built a POI model for the given services with consideration of the major attractions - NRHP, parks, historic and recreational areas – for weighting factors. Then, depending on the accessibility (reduction of flood barriers) and activity of access routes I added the related coefficients to the economic output.

Future scenarios

Economic development rates will affect the flood risks extents and corresponding benefits of the adaptation strategies. I used the growth projections for the four model scenarios to estimate the potential acceleration of the business activity. These are the average annual multipliers representing possible market reactions on the extent of hazard risks. In the model outputs I multiplied the results of the monetary risk assessment per a scenario growth projection.

My approach simplified business operation loss assessment to estimate the impact of the adaptation strategy on the intangible side of the economy – business operation. Thus, I left out physical damages and costs of repairment. HAZUS occupation types and damage values were assigned on the building level and further aggregated at model areas. The dynamics of the economic parameters per occupation type must further be extrapolated using NAICS industry codes. Additional multipliers to identify the trends across the model areas involve accessibility and attractiveness defined based on the walkability index.

Strand 4. NbS economic co-benefits: attractiveness and growth

Recreational and cultural attractiveness

Tourism and recreation flows and trends are highly influenced by the synergy with correlated functions and attractions in the area. Conceptually, even with the same number of establishments allocated in the area, economic benefits can be multiplied by the trends in visitors' attendance due to businesses accessibility. Areas with a rich and diverse presence of recreational and cultural attractions are promoting tourism and encouraging further investment. I assessed this parameter by the visitors' attractiveness per a Model area assessing the density of cultural activities. This attractiveness index per model area is based on the NRHP and Parks datasets weighing the amount of interest per an amenity controlled by the model area. For the scenarios of adaptation these indices are increasing along with the added areas of Nature Based Solutions potentially accessible for a public promenade.

Model areas adjacent to NbS location can be qualitatively assessed in terms of cultural, natural, and view qualities constituting additional recreational attractiveness for the recreation and tourism activities. I turned these qualities into weighting coefficients to estimate the expected revenue generated. Multiplication of the area accessible and attractive for visitors including recreational use protected from coastal floods and the project area with the recreation and tourist use – together enforce potential environmental co-benefits of the project. Then, the economic benefits will be multiplied by these attractiveness ranks identifying potential visitor’s flow following the method of relative value ranking (Emerton, 2014). The weighting coefficients of different shoreline segments are important to estimate the tradeoffs of keeping or altering the land use trends of a model area. Nevertheless, the accurate values of projected economic growth must be assessed based on the visitors spending behavior obtained from tourist operators and local economic development agencies.

Adaptation measures assessment

I finally aggregated and compared loss reduction by each shoreline segment by a model area (defined as functional profile and correlated NbS profile) so that the output of the module explicitly estimated flood adaptation capacities of applied ecosystem-based strategies. The recommended adaptation measures with the corresponding size parameters represent the perimeters of out model areas. They are ranked by the benefits provided to the recreation and tourism economy by the annual output criteria. For each study unit, I calculated the exposed assets by occupation type (RES4, COM1, COM8), operation disruption costs, and mitigation benefits in monetary values and ratio. The next steps in this strand involve adjustment of an ecosystem-based measure design depending on the desired economic growth in the areas prone to hazard risks. The five model cross-sections were modified in terms of elevation, width, and robustness of protective vegetation. Factors considered are land use patterns, navigation routes, and other potential barriers to ecosystems. More information on this module can be found in the Appendix 05 (pp. 134 – 138)

CHAPTER THREE

KEY FINDINGS AND MODEL PERFORMANCE

Linking back to the research questions, I focused this part of my paper on the study findings classified in three categories - how the tourism sector operations are affected under the recent sea level rise projections, what NbS adaptation strategies are suitable to reduce and mitigate those risks and losses, and how the economic benefits of the prevented loss of operation for the sector of tourism and hospitality vary by perimeter solutions over planning scenarios. I presented the main findings to inform further development and implementation of ecosystem-based solutions in the study area and understanding of their dynamics and potential effects in other coastal areas at risk. The model performance and other technical data and findings related to the GIS/ Grasshopper model are explicitly described in Appendices.

Model approach

The complexity of interests and tradeoffs that correspond with coastal flood protection in the context of uncertainties were integrated in this parametric algorithm. Most importantly, the interface of Grasshopper and Rhino allow to adjust and improve this set of factors further reacting on the evolving knowledge. Thus, my model contributed to the gap in comprehensive methodologies of the NbS assessment. Research gaps related to complexity and scientific uncertainty of sea level rise projections and effects of green and hybrid coastal adaptation are also partially addressed with this approach. Further developing this methodology and scenario-based approach will help to address these gaps and incorporate the latest knowledge on sea level rise and extreme storms projections. This in turn will allow decision-makers to consider flexible approaches to updated knowledge.

My modeling approach clarifies the local economic impacts of ecosystem-based solutions introducing focused metrics of performance and economic impacts of NbS. Resilience implementation barriers and maladaptation emphasized the need for collaboration, data quality, and midterm monitoring of results, that is possible with scenario-based approach (Aerts et al., 2014). Thus, the model also improves transparency to communicate solutions and their consequences with the stakeholders and especially local communities.

Flood risk exposure of commercial sector. Tourism and recreation

As noted in the literature review summary, flood exposure of the residential sector is more explored than flood exposure of commercial facilities (Barbier et al., 2013; Kousky et al., 2021). The first module of my algorithm "Flood impact assessment" identified the growing rates of Sea Level Rise affecting tourism economy in the area of interest. According to the algorithm flexible functionality, similar assessment can be conducted for other cities and economies considered in the National structure inventory or other local inventory databases. This contribution is essential for the further development of investment frameworks capturing the values of proposed solutions to potential co-investing businesses (Levy & Herst, 2017; Source).

Among the six areas analyzed and compared, the most significant rates of exposure and vulnerability are demonstrated in the central Model Areas (3-5). The reason for that is not only the overall exposure to winds, waves, and storms, but mostly the patterns of tourism sector allocation and its gravitation towards the coast as it is shown in the Figures 14 and 15.

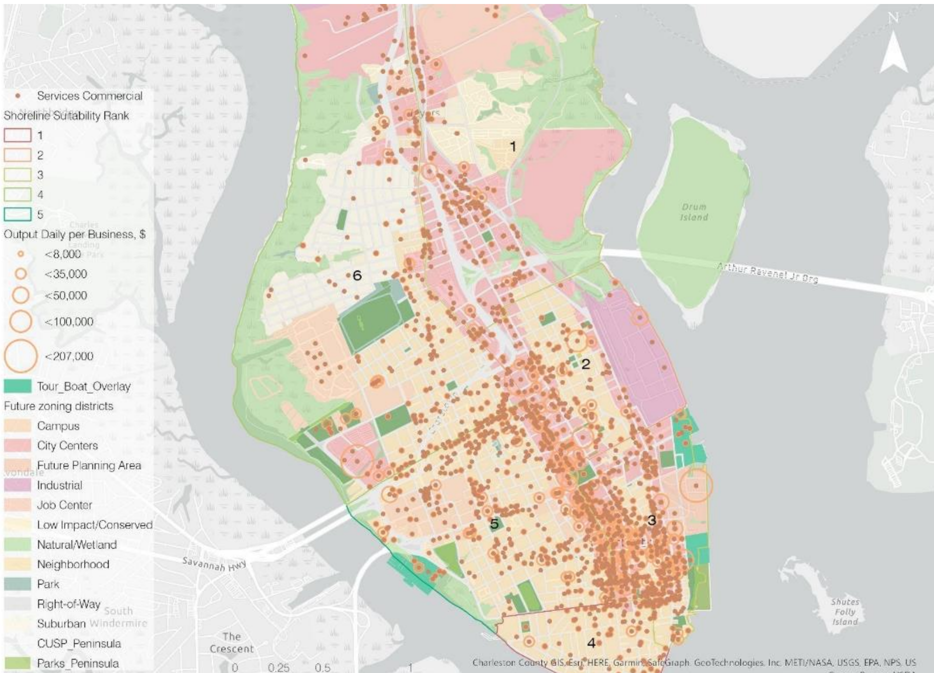


Figure 14. Allocation of tourism sector services in six model areas

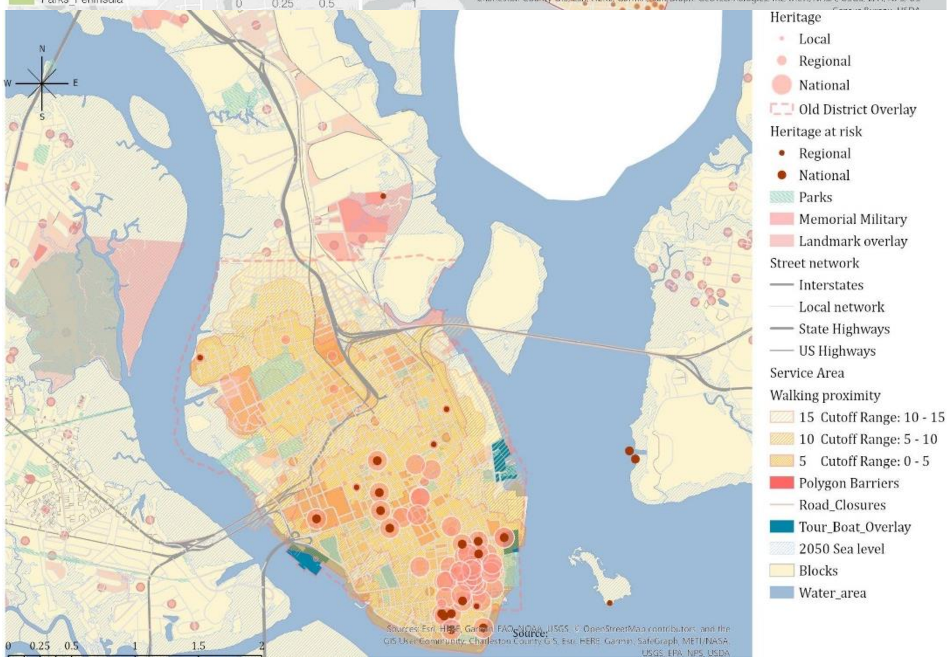


Figure 15. Tourist attraction on the Charleston Peninsula (NRHP, Charleston GIS services, 2022)

Exposure of tourism and recreation

The tourism sector constitutes 736 out of 2200, or 33.45 % of all the commercial facilities in the area of interest (Figure 14). Breaking down this data slice, it can be seen how the exposure is distributed among three occupation classes. Retail makes 43.48% of the tourism facilities, entertainment - 41.71%, and lodging - 14.81%. Within their subcategories, the exposure rates vary across the scenarios. Thus, the short-term scenario demonstrates the highest flood exposure of the entertainment sector - 7.17%, and the 2 and 4 scenarios show exponentially growing exposure of lodging - 50.46% and 64.22% respectively.

The tourism and recreation business establishments are distributed between the 6 model areas as 6.79% - 12.64% - 36.68% - 5.98% - 26.36% - 11.55%. the highest concentration of Tourism establishments is in the Model area 3 (0.68 per acre), which by default makes it more vulnerable in terms of economic losses. At the same time, existing site terrain and proximity to the shore contributes to vulnerability to SLR and storms as we see from the MA 5. Overall, the ratio of tourism/ recreation to all commercial services is the highest in MA 4, whereas the ratio of services of interest exposed to flood risks to other commercial services exposed to it is on the average 30% with the highest indicators in 4^{th} (Figures 23-25).

Exposure across scenarios

The 1 and 3 scenarios – short-term moderate and business as usual levels of emissions - according to Kopp et al and Climate central projections demonstrate the same levels of flood by 2032. Further the exposure grows exponentially. Depending on the planning scenario, Tourism facilities exposed to both types of flood risks represent from 28.05% (short-term) to 32.11% (long term, medium emissions) and 31.42% (long term, high emissions) of the total commercial facilities in the area of interest. It corresponds with 6.25%, 35.73%, and 43.89% of all the Units of interest in the study area. Also, from 2.31% in the 4.5 to 12.23% in the 8.5 projections of the total tourism facilities on the Peninsula will have to permanently close due to the flood related disruption of operation by the year 2082. This means that 44 commercial facilities, including 17 tourism related business are expected to exit under the moderate emission scenarios, and 297 including 90 tourism facilities - under the high emissions. Above that, the expected number of facilities disrupted with the consequent recovery time by a major storm of a 100-year probability of occurring is 46, 246, and 233 (Figures 16-18).

Figures 16 - 18. Exposure of the tourism sector under scenarios 1-3, 2, and 4 (top to bottom).

These exposure values vary by model areas across three scenarios. The highest percentage of all the tourism sectors exposed to flood risks is allocated in the model area 4 - “Battery and civic center” across all planning scenarios. The most extreme in terms of the number of services exposed are MA`s 5 for the short-term scenarios, and 3 in the long run. From the economic development point of view these results call to prioritize the areas of highest exposure, Battery, in the short-run, and depending on the emission levels by 2032 – either focus the adaptation efforts on area 3 “East Bay” or area 5 “Harleston village/ Marina”. It's remarkable that in both of the areas with the highest numbers of affected services, the Entertainment and Recreation occupation class has the biggest share.

Adaptation potential. Ecosystem and anthropogenic performance factors

Little or no studies addressing both natural and man-made factors for proper NbS suitability assessment – and the suitability assessment of the “Adaptation Strategy” module aimed to contribute to this gap. It also made a step towards transparent and comprehensive metrics of NbS performance (Bridges et al., 2021b; Currin et al., 2019). Specific design considerations of the transects should be further developed based on the model. This module also contributes to better understanding of the NbS benefits for the local business through transparent economic impact modeling as opposed to the “blackbox” CBA approach used by the USACE in evaluating the Peninsula strategy. My accessible assessment sets the framework for the public-private partnership in NbS investment (Levy & Herst, 2018; Spanger-Siegfried et al., 2017)

NbS`s flood risk reduction capacities

The model currently has a level of abstraction capable of illustrating standard parameters of the nature-based structures informed by their suitability for the related ecosystems and optimal flood attenuation capacities. The applied schematic principles of subdivision into “Core” and

"Sponge" parts of an NbS with the related attributes and protective capacities allowed to predict the dynamic nature of vegetation in relation to sea levels over time. These general configurations of perimeter solutions with possible natural adjustments illustrated the major effects of various types of living shorelines. Nevertheless, following the dynamic algorithm of increasing height of a crest along with the expansion of the dikes and levees slopes both underwater and landward – under the SLR projections – the model identified both the protection levels and the "bottle neck zones" of ecosystem-land uses conflicts (see Figure 19).

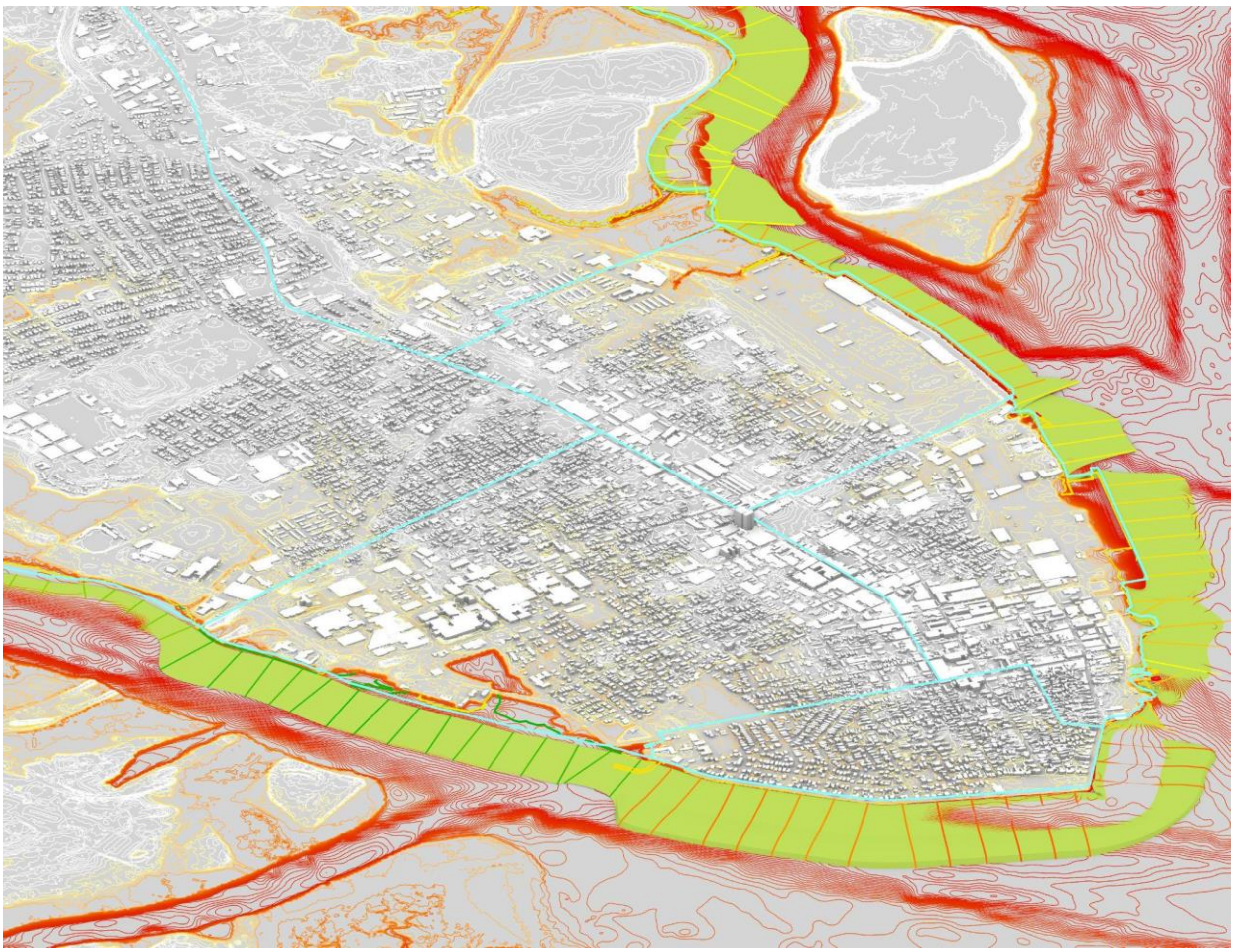


Figure 19. Performance of the Living Shorelines perimeter against SLR and Storm Surge

The inputs I used for the model to measure the levels of protection were configurations of NbS transects and vegetation capacity to attenuate the wave energy (see Figure 27). The crest heights were determined at the levels of 4-6 ft over the MHHW level to gradually enhance the protection from the rising Sea level in the long term scenarios. According to Hazus Model and FEMA records, the levels of floods preventing business from operation and causing the disruption are about 2 ft of water. Figure 20 below shows the levels of water expected to intrude the area under the 1% of annual occurrence extreme flood event.

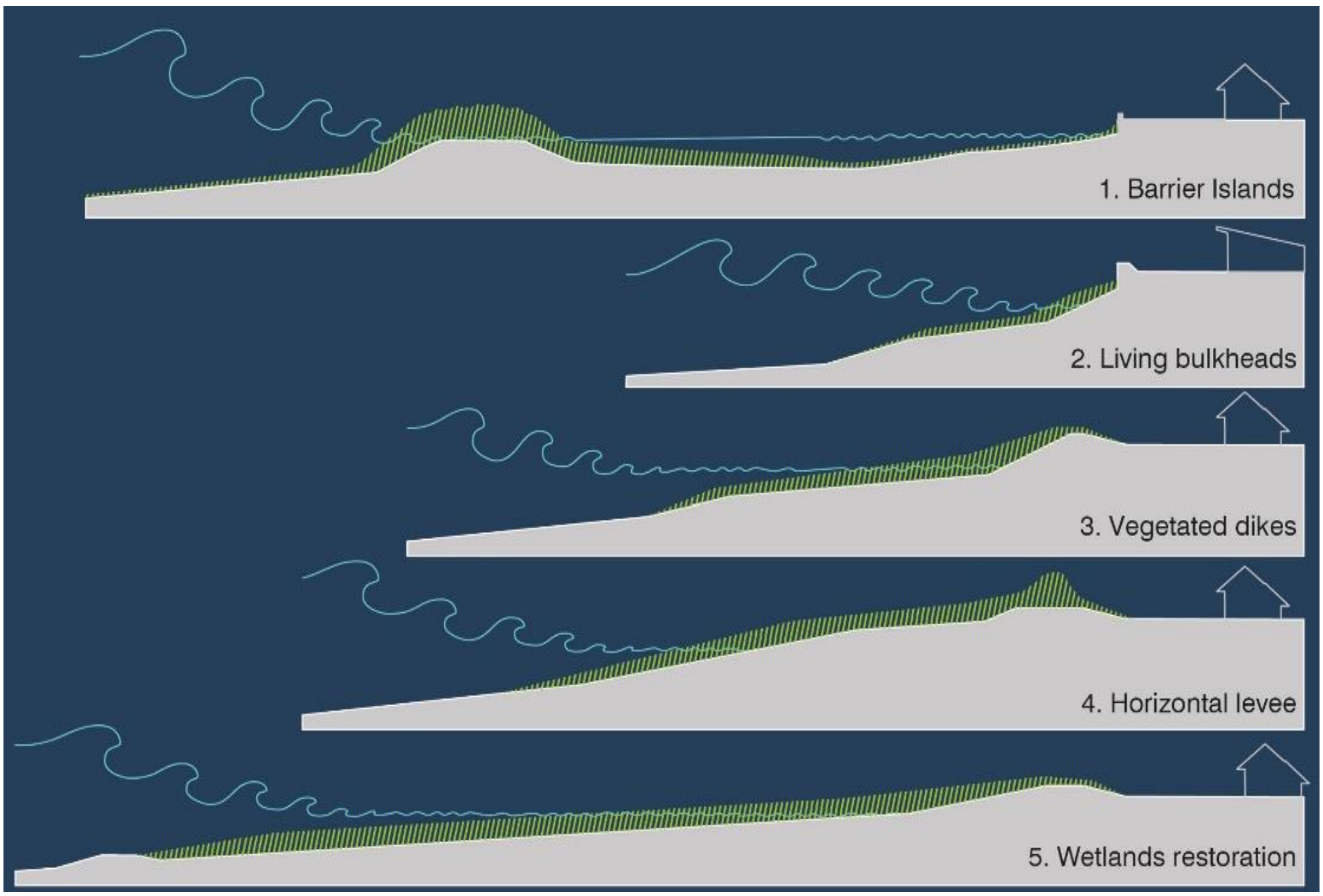


Figure 20. Illustrative transects - Core and Sponge interaction with SLR and SS

Model Areas	**Nb PS Key**	**NbPS type**	**Wave attenuation**	**Disruption elevation with 4-5 ft crest, Sc1-3**	**Disruption elevation with 4-5 ft crest, Sc2**	**Disruption elevation with 4-5 ft crest, Sc4**
1 - NOMO/ East Central	**3**	Dikes and levees with oyster tecture	0.7	-2.53	**0.37**	**1.97**
2 - Wraggborough/ Port	**2**	Living bulkheads with ripraps	0.5	-1.75	**1.15**	**2.75**
3 - East Bay	**3**	Dikes and levees with oyster tecture	0.7	-2.53	**0.37**	**1.97**
4 - Battery/ civic center	**1**	Barrier Island	0.9	-3.31	-0.41	1.19
5 - Harleston village/ Marina	**5**	Wetlands restoration	0.8	-2.92	-0.02	1.58
6 - Wagener Terrace	**4**	Horizontal levee	0.9	-3.31	-0.41	1.19

Table 10. Coastal protection. Vegetation waves attenuation capacity and respective flood depths.

The depths levels considered vegetation density and related attenuation ratio per each of the transects to establish the threshold elevations above the water levels under which the properties experience disruption. Ecosystem-specific reduction levels were then reduced by the heights of the structural elements with the cap of 2 ft over the expected SLR. The areas of limited space to accommodate the solutions slopes, the crests were reduced - that inevitably caused the higher estimated flood thresholds. In assessing the levels of risk reduction the model spatially and volumetrically simulated the Storm Surge and SLR interference with the perimeter considering the land use limitations and the elevations and depths of the high-resolution terrain. Under these assumptions model outputs identified the levels of efficiency of the five NbS as applied to the model areas. Measured in the economic output loss prevented, the performance of the solutions at hand varies depending on the expected water levels and the units of assessment density. Table 11 shows that the highest rates of economic loss per acre across the model areas are attributable to the Barrier Islands and Wetlands Restoration. The lowest performance compared to the other solutions is demonstrated by the bulkheads and horizontal levees. This can be both explained with the lower densities of services and the lower levels of “Sponge” or the ecosystem component of the protection.

			Scenarios 1-3 (2032)				
Model Areas	NbS types	Acre	Prevented Loss, $	Op Loss With, $	Loss mitigation	Mitigation/acre	Mitigation/total
4	1	220.20	2,373,194	0	100.00%	10,777	15.77%
2	2	500.72	544,254	0	-	1,087	3.62%
1,3	3	1,811.03	4,813,196	0	100.00%	2,658	31.99%
6	4	1,999.85	1,574,104	0	100.00%	787	10.46%
5	5	728.92	5,741,744	0	100.00%	7,877	38.16%
Economic impacts by scenarios		5,261	**15,046,492**	**0**	**100.00%**	**2,860**	**100.00%**
							100.00%

Scenario 2 (4.5, 2082)				Scenario 4 (8.5, 2082)			
Prevented Loss Sc2, $	Loss mitigation	Mitigation/acre	Mitigation/total	Prevented Loss, Sc4 $	Loss mitigation, Sc4	Mitigation/acre, Sc4	Mitigation/total, Sc4
216,718,515	100.00%	984,184.91	32.09%	284,387,365	100.00%	1,291,490	6.90%
12,571,992	95.85%	25,107.95	1.86%	514,274,039	99.02%	1,027,074	12.48%
212,686,469	99.60%	117,439.59	31.50%	1,522,955,402	99.75%	1,842,069	36.96%
23,362,424	100.00%	11,682.09	3.46%	454,109,516	100.00%	227,072	11.02%
208,495,846	100.00%	286,033.92	30.88%	1,335,285,259	100.00%	1,831,868	32.40%
673,835,246	**99.79%**	**128,088**	**99.79%**	**4,111,011,581**	**99.76%**	**781,455**	**99.76%**
			99.79%				99.76%

Table 11. Mitigation of risk exposure across planning scenarios.

Across the business sectors the most effectively protected from costly interruptions are the Entertainment facilities. Their major concentrations are allocated in the model areas 3 and 5 both gravitating towards the shore due to the focus on sailing and water sports. The solutions chosen for these areas - dykes and wetlands - also prevent about 70% of the total exits of businesses under both of the long-term scenarios and overall reduce the businesses affected by the storm surge by the same percent. Thus, the combination of vegetated dikes with the wetlands (solution 3) and wetlands restoration (solution 5) are the most effective in exposure reduction across all scenarios. In terms of the benefits per acre, though, the most significant is the barrier island, which again is informed by the concentration of the tourism around the Battery and the top destination for Charleston visitors (Figure 21). Nevertheless, as a protective measure, the Living breakwaters prove their effectiveness along with the potential benefits for the water recreation.

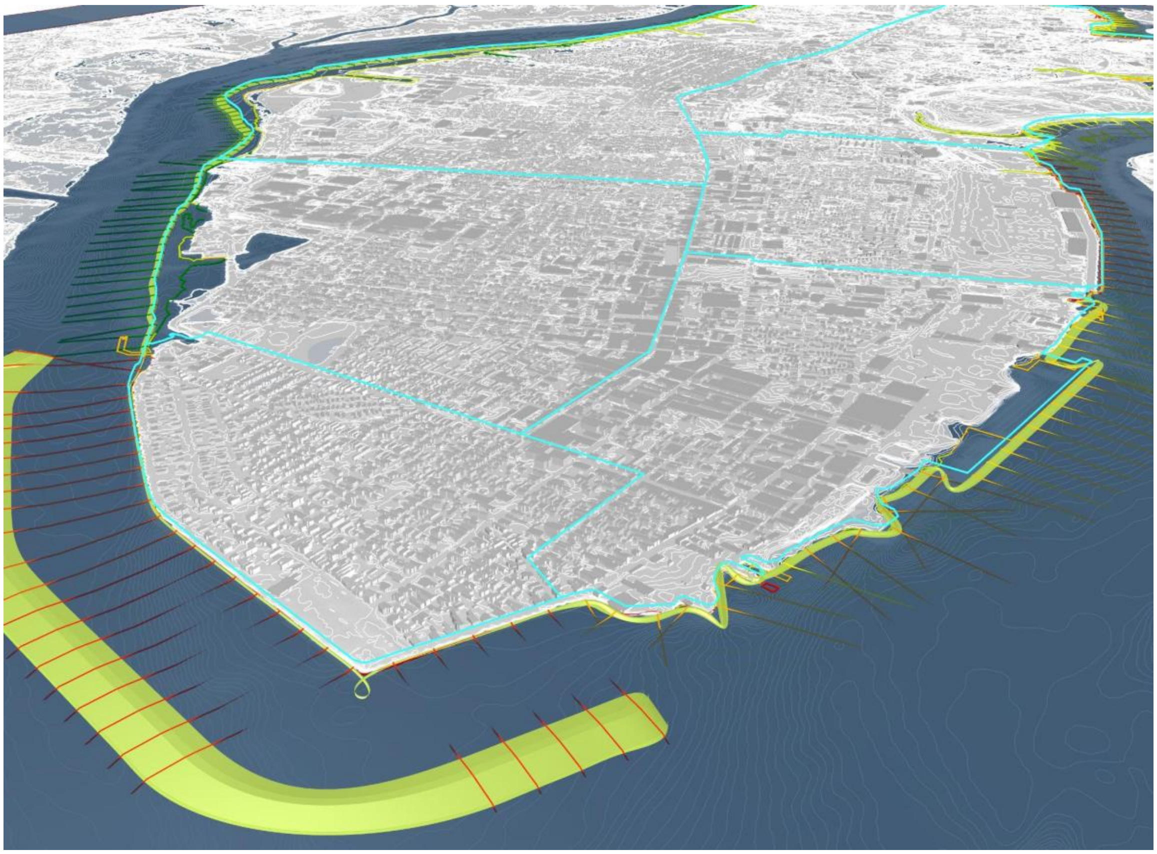


Figure 21. Mitigation of risk exposure in the Model area 1

Urban development patterns affecting the exposure

The current zoning as applied to 2032 scenarios and the future zoning code as applied to 2082 are the defining factors limiting the required risk reduction due to spatial barriers. This links us back to the literature review takeaways on the major factors affecting performance of NbS – urbanization as demonstrated with zoning codes, development, and transportation uses. As such, the major limits for the NbS transect to extend to the suitable for the ecosystems length is represented by the navigation corridors and intensive land use – industrial and transportation especially in the MA`s 2 and 4. The MA 4`s shoreline has shown the lowest level of suitability for the NbS solutions due to the high wave energy, intensive land uses, and other factors, and was able to accommodate the extensive cross-section of the typology 1 – Barrier island with the consequent highest levels of wave attenuation. The MA 2 is limited in space and cannot afford the barrier islands due to the port logistics. Therefore, the existing uses reduced the attenuative capacity of NbS, especially under high emission scenarios.

Economic benefits for the coastal economies

As previously discussed, the NbS interventions are capable of significant reduction of SLR and coastal storm floods exposure. Nevertheless, they are limited in the rates of adaptation to the changing water levels, and the high emission scenario shows exponential growth in numbers of remaining losses after adaptation over the model areas. If the 10 years lifespan of the project is expected to completely prevent the operation disruption loss, moderate emission 50-years projection will face over 1B of loss and the high emission - 9B losses concentrated around 1-3 Model Areas. The economic benefits of living shorelines are compared in Table 12-14.

Model Areas	Acre	NbS types	Prevented Loss Sc1-3, $	Op Loss With, $	Loss mitigation	Mitigation/acre	Mitigation/total
1	1,413.70	3	153,889	0	100.00%	108.86	1.02%
2	500.72	2	544,254	0	-	1,086.95	3.62%
3	397.33	3	4,659,307	0	100.00%	11,726.66	30.97%
4	220.20	1	2,373,194	0	100.00%	10,777.40	15.77%
5	728.92	5	5,741,744	0	100.00%	7,877.06	38.16%
6	1,999.85	4	1,574,104	0	100.00%	787.11	10.46%
Total EIA SS 1,3	5,261		15,046,492	0	100.00%	2,860.16	100.00%

Model Areas	Acre	NbS types	Prevented Loss Sc2, $	Op Loss With Sc2, $	Loss mitigation, Sc2	Mitigation/acre, Sc2	Mitigation/total, Sc2
1	1,413.70	3	19,123,053	0	100.00%	13,526.93	2.83%
2	500.72	2	12,571,992	544,254	95.85%	25,107.95	1.86%
3	397.33	3	193,563,416	861,863	99.56%	487,165.11	28.67%
4	220.20	1	216,718,515	0	100.00%	984,184.91	32.09%
5	728.92	5	208,495,846	0	100.00%	286,033.92	30.88%
6	1,999.85	4	23,362,424	0	100.00%	11,682.09	3.46%
Total EIA Sc 2	5,261		673,835,246	1,406,117	99.79%	128,088.11	99.79%

Model Areas	Acre	NbS types	Prevented Loss, Sc4 $	Op. Loss With, Sc4 $	Loss mitigation, Sc4	Mitigation/acre, Sc4	Mitigation/total, Sc4
1	1,413.70	3	82,274,846	153,889	99.81%	58,198	2.00%
2	500.72	2	514,274,039	5,113,855	99.02%	1,027,074	12.48%
3	397.33	3	1,440,680,556	4,659,307	99.68%	3,625,940	34.96%
4	220.20	1	284,387,365	0	100.00%	1,291,490	6.90%
5	728.92	5	1,335,285,259	0	100.00%	1,831,868	32.40%
6	1,999.85	4	454,109,516	0	100.00%	227,072	11.02%
Total EIA Sc 4	5,261		4,111,011,581	9,927,051	99.76%	781,455	99.76%

Tables 12-14. Economic benefits and residual losses for planning scenarios with the adaptive perimeter. Short-term scenarios (top), long-term RCP`s 4.5 (middle) and 8.5 (bottom)

Monetary values of the ecosystem services

Under the short-term scenarios, the highest benefits in loss prevention per acre are concentrated in the Model Area 3 East Bay and are provided by Vegetated Dykes. This is a possible consequence of the combination of structural and soft flood protection measures and higher concentration of the business establishments in this area. At the same time, long-term scenarios prove the growing benefits of the Barrier Islands and Wetland Restoration. As such, the mean parameter of tourism sector operation loss Mitigation per acre in the short-run is 2K with the highest of 11.8K for the Vegetated dykes. For the long-term scenarios it increases to 128K average and peak 984K and 487K for the Barrier Islands and Dykes and 781K average and peak 3.6M and 1.8M for the Dykes and Wetlands for the 4.5 and 8.5 scenarios respectively.

The Economic Impact Module outputs provided the fine grain classification of exposure and loss with and without a project to assess the benefits per sector. The allocation of services in Charleston Peninsula showed the major share of retail trade among the chosen category (320/736), whereas the most affected sector, as measured by the number of businesses disrupted, is Entertainment and recreation. It also has the highest attributes of operation loss and benefits of its prevention. As such, entertainment makes 22/46 and 118/263 share of businesses exposed to flood risks in the short and the long-term scenarios correspondingly with the 99% reduction of these risks by the NbS examined. This trend comes along with the assumption of visitors' behavior patterns and especially outdoor activities gravitating towards the shore.

Additional tourism and recreation aspects of growth.

The outputs of the model then were adjusted with the indices of attractiveness per model area using land use classification. The growth projections were based on current and future zoning with the correlated ranks of intensity from 1 to 5. The Attractiveness coefficients reflected synergies between tourism units of assessment and the other recreation-related attractions within the areas of analysis. These include NRHP places weighed by their significance, and parks and tourism overlays with the respective attributes of area in acres and activities to represent the magnitude of attractiveness. As Figure 22 shows, the different NbS configurations offer various coefficients of attractiveness based on the same parameters as the parks and recreation areas - accessible for visitors area in acres and potential activities combined with this perimeter solution. At this level of development, the model parameters per solution were approximated with the widths above sea level and shoreline length.

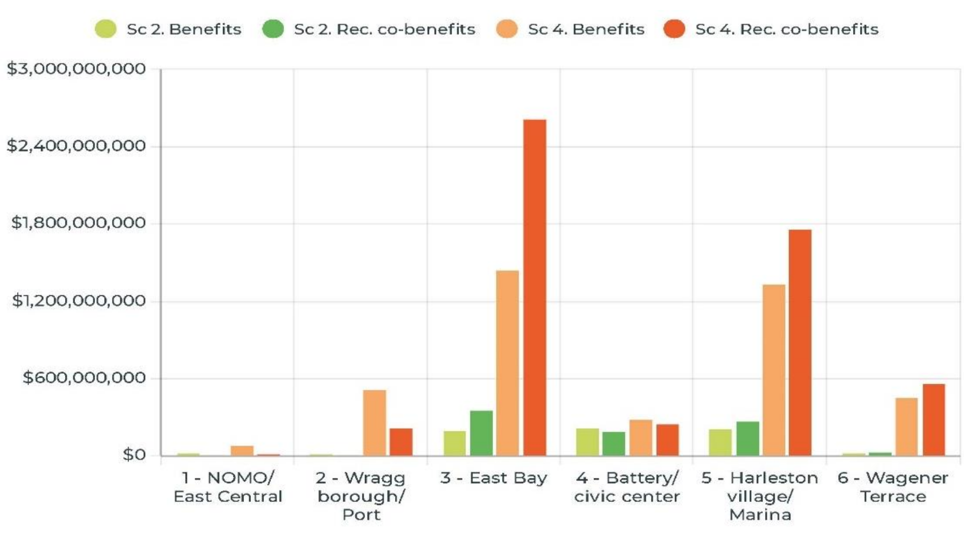
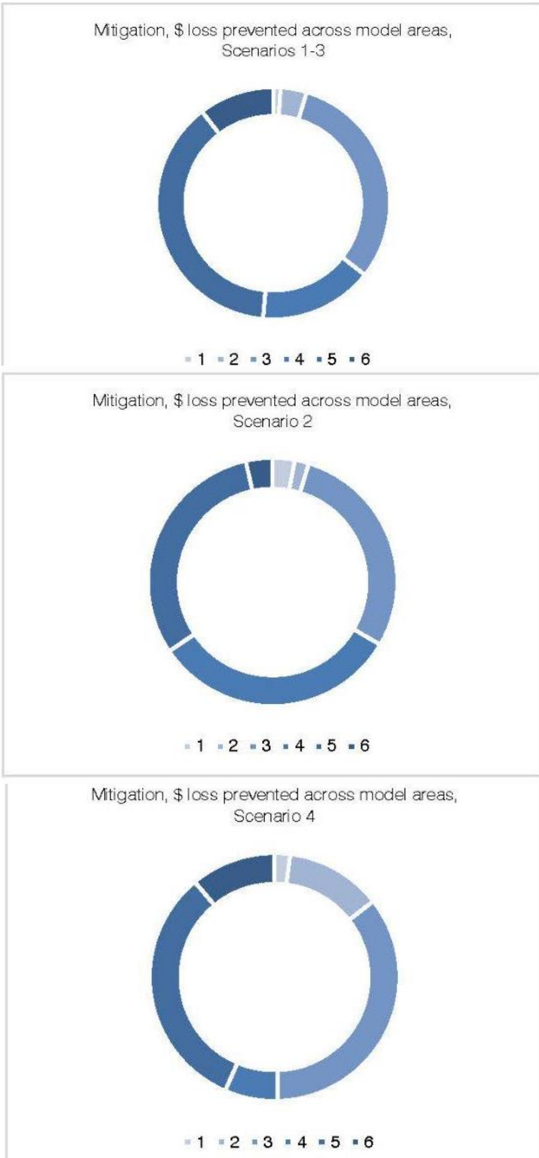


Figure 22. Attractiveness and Growth coefficients per a Model area



Figures 23-25. Economic values of flood mitigation provided by the NbS`s in $/acre per a model area

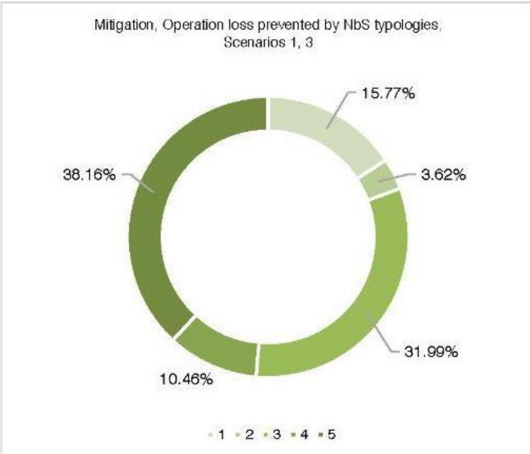
Scenario-based variation

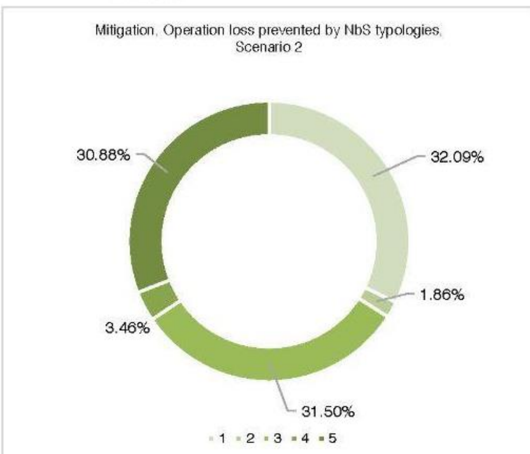
The scenario-based approach of my model created a decent response against sea level rise and socioeconomic uncertainties (Davis et al., 2015; Temmerman et al., 2013; Moraes et al., 2022). My study took a separate module from the FEMA Hazus CBA, and introduced the weighed ranking of the recreation attractiveness to account for ecosystem services provided by proposed NbS. (Wharton, 2020).

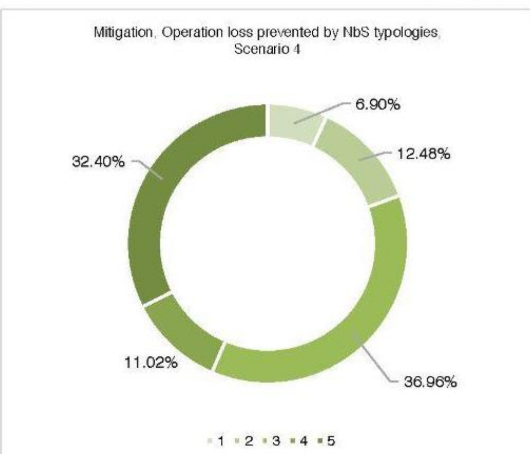
Adaptation and tourism growth

The additional green areas introduced by NbS can bring better ecosystem values and view characteristics to a site thus causing more visitors. As the Tourism report states, the main visitor flows in the area follow the clusters of historic and natural attractions (Office of Tourism report, 2022). The results I obtained with this model show how the short term expected risks and mitigation benefits refer to the importance of implementing Wetlands restoration measures in the model area 5 to protect the greatest amount of the tourism and recreation sector. By the time of 2032 the updates on emission scenarios will allow the 2082 timeframe priorities to be chosen according to the benefits and community needs. The following Figures 23-25 illustrate the potential priorities based on the economic benefits.

Risk thresholds informing land use practices





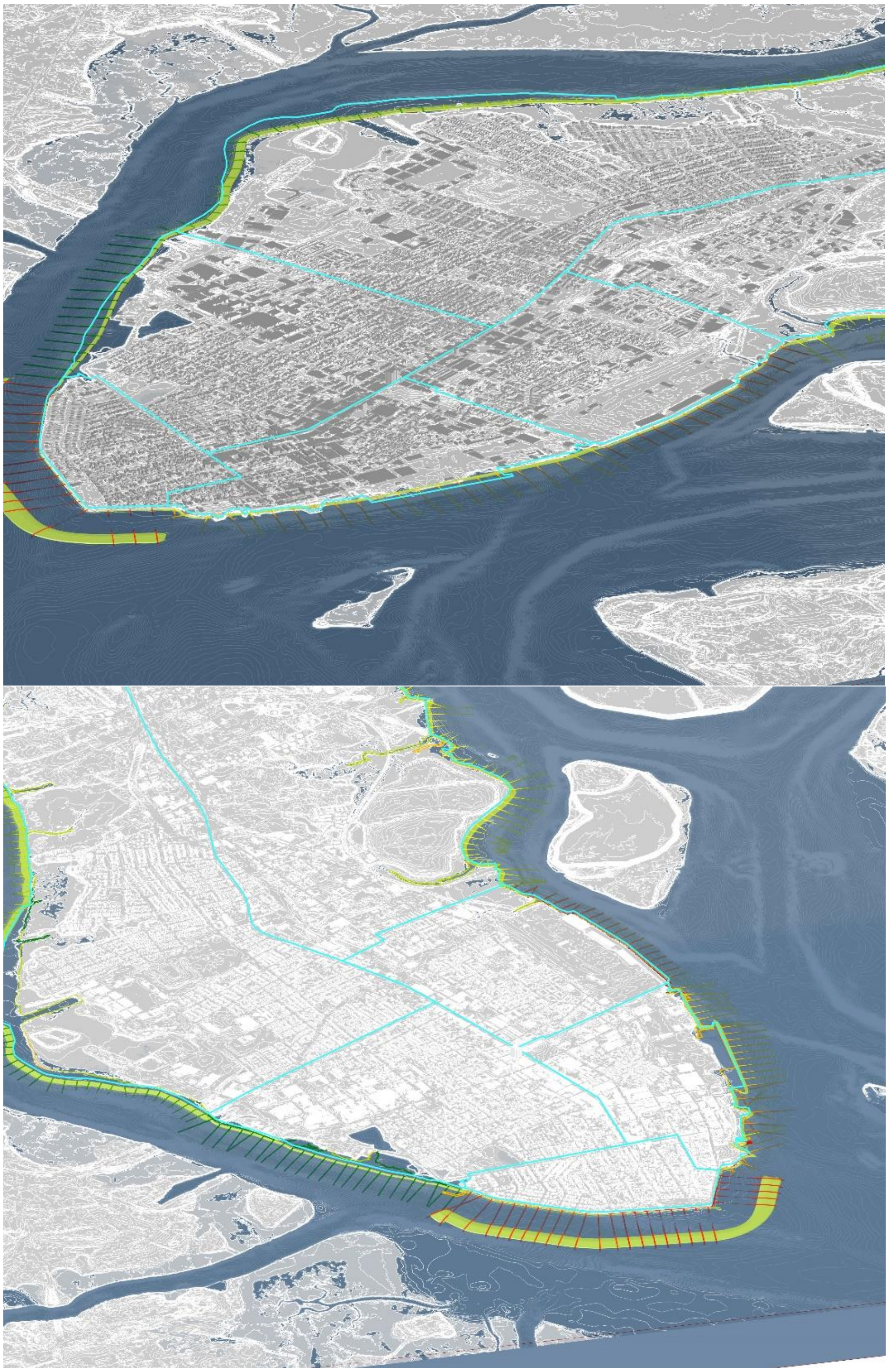


Figures 26-28. Economic values of flood mitigation provided by the NbS`s in $/acre per an NbS type

Prioritizing the strategies is essential to inform decision making on coastal adaptation due to the high upfront costs of the interventions, and the rapidly increasing magnitude of flood risks in the coastal areas. The final strand of the NbS model provides the data on benefits from risk mitigation distributed across the sectors, shoreline segments, and model areas. As we can see from the charts, each of the five solutions examined in this study contribute to the total risk mitigation differently over time. Thus, we see how the Vegetated Dykes and Wetlands both make about ⅓ of the total value for Charleston Peninsula. Focusing on their implementation in the short-term will greatly protect the tourism and recreation sector as an essential driver of Charleston wellbeing and resilience. As the risks exacerbate in the long-time sea level rise and storm surge occurrence projections, the protection of areas with the highest concentration of businesses start to take a bigger share (See Figures 26-28).

Thus we can see that Scenario 2 output is almost evenly divided between the benefits from 01

Barrier Island, 03 Living dykes, and 05 Wetland restoration. Scenario 4 points at prioritization of the most flood-prone areas protection with the living dykes - as both NOMO and East Bay will experience the major probabilities of floods induced by storms. These outputs can be further adjusted and compared with the modification of the NbS transects geometry and vegetation characteristics. These results will potentially be the tool for assessing the choice of most suitable mitigation strategies based on the local shared community values and priorities (See Figures 29-31).



Figures 29 - 31. Economic benefits for the tourism sector under the scenarios 1-3, 2, and 4 (top to bottom)

CHAPTER FOUR

POLICY IMPLICATIONS

Recommendations for Charleston

A possible method to reconsider the Peninsula study

The model addresses the issues omitted by the USACE Charleston study, offering higher level comprehensive estimation to inform the dialogue of decisionmakers with the community. The chosen timeframes of the years of 2032 and 2082 are aligned with the USACE study and correspond with the 10- and 50- years as short- and long-term planning horizons. The models of flood impact assessment, designing the perimeter adaptation, and measuring its economic impacts are different. These models communicate the local business interests in the area and assesses the ecosystems from this perspective. Natural Protection and local smart green infrastructure adapted by commercial facilities can provide even better conditions for seasonal visitors and smooth the disadvantages of inundation in the streets. Thus, the model results can help empower and encourage the commercial sector to support the ecosystems.

Tradeoffs of ecosystem versus the economies

In Charleston, tourism and hospitality make a significant contribution to the local economy, and therefore cannot be displaced under the hazard risks. The dynamics of zoning proposed by the current comprehensive plan provide for more resilient pathways potentially reducing the exposure (Charleston City, 2021). Relocation or adaptation decisions shall be made considering the comparison of costs and benefits of adaptation, relocation, or the retrofits lowering the impact. This will take the question of heritage preservation versus coastal ecosystems protection into consideration by decisionmakers and communities. The model results support decision-making through informing the major land use and climate factors of allocating the commercial services. It identified zoning classes with the highest densities of exposed businesses. Depending on the desired level of risk reduction and socioeconomic priorities, the model provides a blueprint to regulating business allocation and the future land use.

Storm surge risks due to the temporal character and relatively low probability of occurrence caused mostly temporary losses across the model areas. Though the results showed that rising sea levels in “without the project” scenario caused complete exit of services under the higher emission scenarios and considerable exacerbation of loss over the time and emission scenarios. NbS effectively reduced these consequences, so none of the scenarios results in permanent preventing businesses from operation in “with project” model results. Thus, I can state that the properly designed NbS as applied to the suitable areas mitigate the adverse effects of SLR by 90 - 100 %. Figures 23, 29-31 demonstrate the performance of NbS in preventing disruption and permanent closure of businesses with Wetlands (5), Vegetated Levees (3), and Living Breakwater (1) being the leaders across the scenarios.

Clear and transparent for the communities

The model I developed has a high importance for the additional communities` engagement in decision-making on the Charleston Peninsula, as they, too, are repeatedly affected by coastal surge and tidal floods. While the federal project of protective seawall closes the immediate area from hazard risks with a high reliability, it has multiple disadvantages for the adjacent coastlines, and even for the Peninsula itself in terms of its visual and ecosystem characteristics. The broadly shared public stance for alternative solutions needs more robust justification to be competitive with a conventional approach. My model assessed ecosystem services of proposed NbS`s in terms of damage prevention and longer indirect economic impacts. It has shown how different ecosystem-based approaches vary in the loss prevented and benefits generated. These two aspects are assumed to be considerable arguments for the developed coastlines with the established cultural infrastructure and high attractiveness for visitors.

Charleston Peninsula Flood Vulnerability Assessment (USACE, 2017-2022) developed a fine-grain building-level assessment utilizing NOAA sea level projections and FEMA Hazus model for allocating flood protection infrastructure. Although, as critiques show, it lacked the transparency in the methods and factors involved in the economic and risk assessment. The reduction of storm surge along the rivers in Charleston can vary depending on the specific location and characteristics of the river and the surrounding topography, which the USACE study does not clarify in the takeaways. The study also did not incorporate the latest SLR models, which can cause the false results as the climate continue changing. The parameters of my adaptive model are easily deliverable and can be further updated with the more recent knowledge on sea level rise and storm surge contributors. This in turn will give the city managers the tools to adaptively regulate the levels of protection involving stakeholders in the process.

Land Use planning

An essential outcome of this Living Shorelines Generative Model is identifying conflicting zoning practices. Spatial and volumetric interface allowed to find the bottleneck areas where the space required for an NbS to develop is limited by the high intensity uses such as industry, transportation, or utilities. By evaluating the percentage of reduced protection capacity due to the hard boundaries of these areas, the model helps inform the choices to “soften” the edge, or potentially downzone an area of conflict. The capacity to mitigate coastal storm surge is limited with the hard structure of the shore and intensive land uses. It must be considered that the “false sense of security” provided by the perimeter adaptation has to be properly treated by the city managers in regulatory restrictions for the further allocation of the services in the areas of highest risks – those located below the projected SLR levels potentially affected by higher water levels resulting in the overflows. Although it needs more local-specific data to evaluate the local business operation and recreation benefits in better detail.

Application to other areas

Adaptive approach

The GIS/Grasshopper algorithm developed with this study has multiple implications for the risk assessment, adaptation modeling, and economic loss and benefits assessment with the high levels of accuracy. The processes simulated and parameters obtained include flood risks, damages for various types of occupation classes and land subdivisions, as well as the adaptation strategies and their economic impacts over time. Adaptive approach and drag-and-drop interface with unlimited opportunities for input data and appending analysis strands created a generative tool updating along with the updating data and applicable to multiple locations.

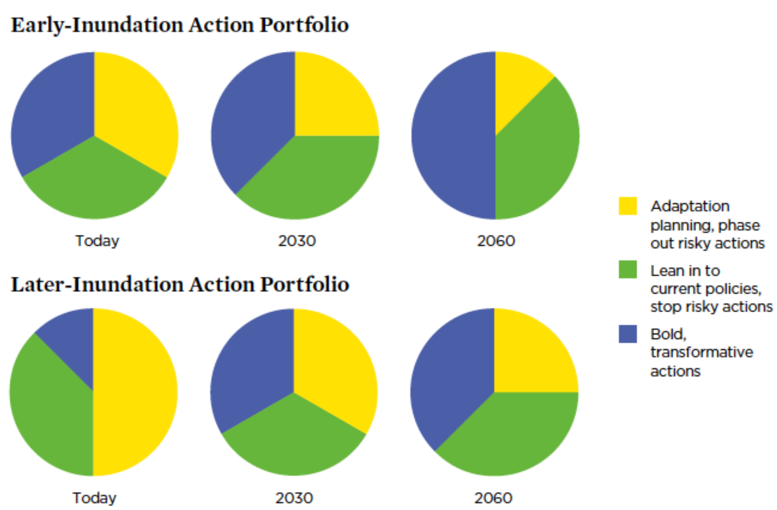
Types of risks

The most important feature of this model is its adaptive comparison of action-no-action choices over the climate change projections and an array of the timeframes. The model proved its applicability and performance in combining a multitude of factors affecting the choice of the adaptation strategy. Notwithstanding its major goal of informing, allocating and designing of the living shorelines, another set of inputs can generate structural alternatives as well. This addition can possibly simplify the process of comparing the most feasible and effective adaptation strategies under the conventional Cost-Benefits assessment. Moreover, the simplicity and transparency of the model framework allows decision makers to weigh various factors of choice numerically based on the choices of local communities and adaptation scenarios. These adjustments help more accurate approximation of loss/ benefits correlation along with the resulting spatially explicit visualization of the resulting flood risks and recreation benefits. These output formats and communication languages are helpful to deliver the consequences of each of these scenarios to various groups of actors visually, quantitatively, and qualitatively.

Areas of application

Broader geographic application and sensitivity testing of the model can also work as a tool to refine the existing knowledge of the NbS flood mitigation benefits. Comparing the multiple locations by the NbS performance can allow state actors to prioritize the application of various types of the Living shorelines and potentially save the limited resources as Figure 32 shows. The first priority areas of its application include the list of the chronically inundated counties highlighted in the report of the Union of Concerned Scientists (UCSUSA, 2017)

Figure 32. Scenarios of the early and later inundation action (UCSUSA, 2017)



The model can be applied in the coastal cities in the US and abroad after testing it in different climate and socioeconomic conditions and refining the method and data input strands. It can help local authorities perform the rapid evaluation of the NbS as alternatives or complimentary solutions for the traditional gray coastal defense. It informs land-use and urban design solutions based on economic performance and tradeoffs of their operation.

Broader implementation for tourism and other commercial sectors

The Living Shorelines generative model has a broad implication as the approachable and flexible tool for first approximation of the nature-based coastal adaptation. The script developed for this research focused on the interactions between living shorelines and the economy of tourism. Nevertheless, using the local input data and choosing other occupation types, it is possible to compare the other economic fields, their risks, protection, and benefits from NbS based on the geographically specific site parameters. This approach is effective to apply to the major economic sectors in the coastal flood areas as it stimulates active business community response and public discussion. It also contributes to the recent globally acknowledged efforts to internalize the costs of resilience. It helps finding the ways to co-fund NbS with support of potential beneficiaries by providing monetary values of the potential benefits. It also informs the business owners on the risks and adaptation or relocation of various types of uses. The outputs of the last module can be used for designing investment strategies such as value capture and environmental impact bonds. The study fills in the gaps in methods of economic impact assessment and funding modeling attracting the resources of the private sector (Levy & Herst, 2018; USCUSA, Spanger-Siegfried et al., 2017).

MODEL LIMITATIONS

The model has its limitations as an experimental analysis and decision-support tool. Firstly, this is the issue of various models applied in this research integrated in one complex model. This might cause compound errors with each new analysis strand (see Figure 07). Greater uncertainties might be identified between the stages – those are the attributes of the data accuracu, model assumptions, levels of abstraction, and margins of uncertainty. The model is applied in Charleston, whereas other areas can have different local factors to consider. This will take better integration of the data imports and extended computational resources. The other questions of internal validity may arise due to the knowledge gaps in NbS` attenuative capacities. The weighing principles should be defined more clearly based on the community priorities and further research. Suitability module and the choice of solutions` profiles need better simulation of the geomorphologic, hydrologic, and biophysical dynamics. Finally, economic evaluation of ecosystem-based services inevitably deals with the questions of over- or underestimation of their values due to the lack of long-term monitoring and observation-based data.

To address the issues of uncertainty, I used a flexible algorithm-based tool of Grasshopper, allowing to analyze each of the strands separately and troubleshoot the issues within the model as opposed to running all the GIS-based analysis from scratch. It helps integrate the updating and evolving data within the established model design and easily adjust the design in case of identified errors. Another uncertainly mitigation tool considered is scenario-based approach subdividing a strategy into several future pathways also allowing to adjust the smaller-scale sets of attributes. Finally, the algorithm will be further tested with the broader geographies and types of uses.

CONCLUSION AND FURTHER STEPS

The research gaps contribution

I was able to incorporate a broader range of suitability factors in my adaptation strategy choice module. In this step I focused on the natural and human-made conditions needed for the living shorelines rather than the economic and social need in coastal ecosystems as previous studies mostly did. I took this approach to balance the community and ecosystem needs and minimize the economic risks related to the improper site selection for sensible natural protection.

The results over the four scenarios provided the results under moderate and high-emission scenarios in a short and long term of the project lifespan. The levels of flood risks obtained from the latest models of Kopp et al (2017) and Climate Central for local tide gauge stations (NOAA, 2023), as well as the building level data allowed adaptively evaluate the protective capacities of the NbS options with the high level of accuracy of the risk exposures.

The lack of the local funding sources and economic impacts represent the significant barriers to ecosystem-based coastal adaptation. This transparent integrative economic assessment framework can potentially operate as an alternative to a complex and obscure cost-benefit assessment. The weighed ranking of recreation attractiveness and suitability factors have a substantial level of abstraction, though allow the communities to manifest their priorities.

The potential threats require closer attention on the further steps of the model development and the actions to prevent induced development following the restored ecosystems and natural shores. Thus, to protect the living shorelines from development pressure there must be rules and regulations implied prior to implementation to restrict further urbanization seaward and continue gravitating towards retreating and downzoning of the coastal area.

Further testing with other solutions and geographies

The method of assigning the NbS profiles by a shoreline suitability rank needs further elaboration based on the transect performance, its better spatial snapping to the topobathymetry, and specific local environmental and geomorphologic data (as such – see InVEST and CLIMADA). This will help mitigate the external validity issues and extend the applicability of the model in a broader range of coastal cities both in the US and abroad. These include but are not limited to the US cities highlighted in the reports of the Union of Concerned Scientists (UCSUSA, 2017), Amsterdam and Venice Metropolitan Areas as major historic cities at risk of coastal floods. Further tests will define the correlation and magnitudes of the tourism economy towards the risk exposure areas.

Further steps towards Building with Nature and Living with water

Contemporary cities need to make the choices in terms of further adaptation of the coastal communities against the accelerating flood risks. The relocation or protection of tourist business establishments is essential for the future economic resilience and the image of a city. Together with the further in-depth cultural and economic assessments this model supports the communities in prioritization of their choices. Core tangible and intangible assets, visitor behavior and major sectors constituting the balance of local economy – these are the factors enforcing the research-based generative approach to designing resilient shorelines. The model has a great potential for increasing resilience against climate change through the informed risk exposure reduction. These are the steps the coastal cities need to make today towards better understanding and active implementation of the principles of building with nature approach to develop and apply the best practices allowing future generations to successfully learn how to live with water.

APPENDICES

Appendix 01

Sea level rise scenarios

USACE Peninsula study scenarios

The latest efforts in flood mitigation planning such as USACE Peninsula study and Louisiana coastal protection masterplan, involved local tide stations observations and expected high tide flood depths (CPRA, H2, White et al., 2021). USACE data for Sea Level Change are gathered from the NOAA Center for Operational Oceanographic Products and Services Application Programming Interface based on observed changes in MSL and SLC projections of USACE, NOAA, and the Coastal Assessment Regional Scenario Working Group. (USACE, 2022, Table 3.3.2.1; CO-OPS API; Sea Level Tracker). By the year 2032 the incremental RSLC rates based on NOAA projections identified the level of 0.56 feet is expected for intermediate rate of sea level rise and 1.01 feet for high rate of sea level rise. The 50-year life of the project correlates with the intermediate rate of 1.65, and the high of 3.93 feet. According to the National Oceanographic and Atmospheric Administration, higher average sea levels correlate to higher storm surge elevations. In the year 2082, assuming a high rate of sea level rise, a 9 ft NAVD88 storm surge inundation would be a 20% Annual Event Probability event. (USACE, 2022).

Climate central probabilistic flood risk model

My study utilized the latest sea level projection models to assess the risks with greater accuracy and inform the decisions accordingly. Climate Central has integrated future projections with local data according to Kopp et al. (2017) that included Antarctic physics from DeConto and Pollard study (2016) as shown in the Figure 33.

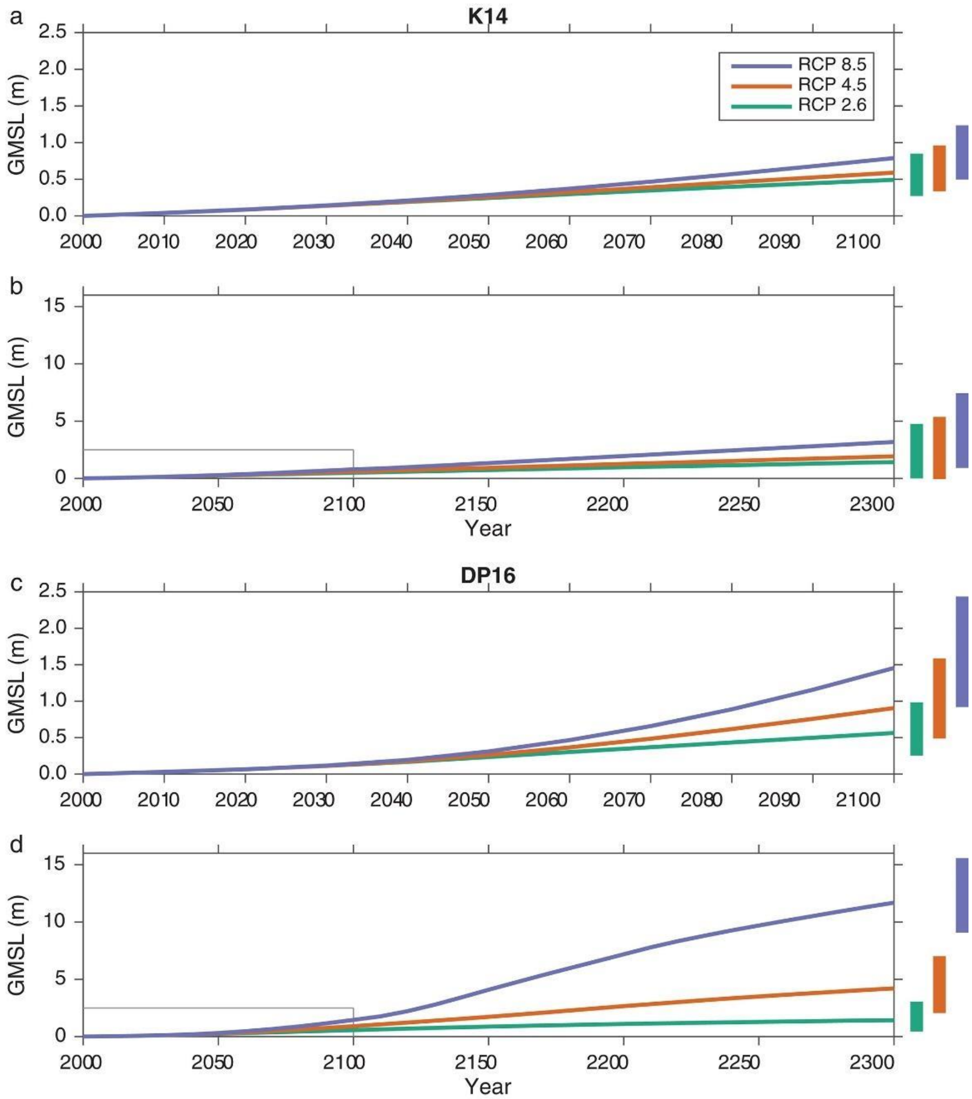


Figure 33. Kopp et al., 2017. Projections of global-mean sea-level (GMSL) rise for three RCPs under probabilistic framework of Kopp et al. (2014) (a, b) and Antarctic melt model of DeConto and Pollard (2016) (c, d).

My model considered the SLR and storm surge risks per a scenario year and RCP level. I obtained these levels from the advanced forecast in Risk Finder for Kopp et al. (2017) for SLR and coastal storm surge of 1% probability of occurrence for each of the RCP`s (see Figure 34). The projections are based on different levels of heat-trapping pollution over time - Representative Concentration Pathways (RCPs), as well as different sensitivities of climate and sea level to pollution (Climate Central Surging Seas, http://riskfinder.org). The limitations of the model include natural variability causing sea level fluctuations and departures from projections. The flood depths in this source are measured from the Mean Higher High Water level of the Charleston station (MHHW, 1983-2001 national tidal epoch).

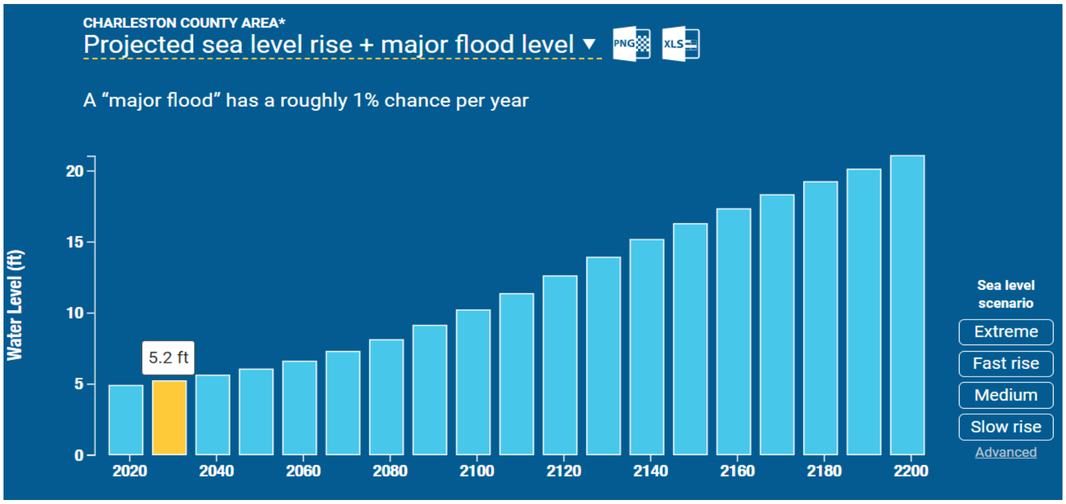
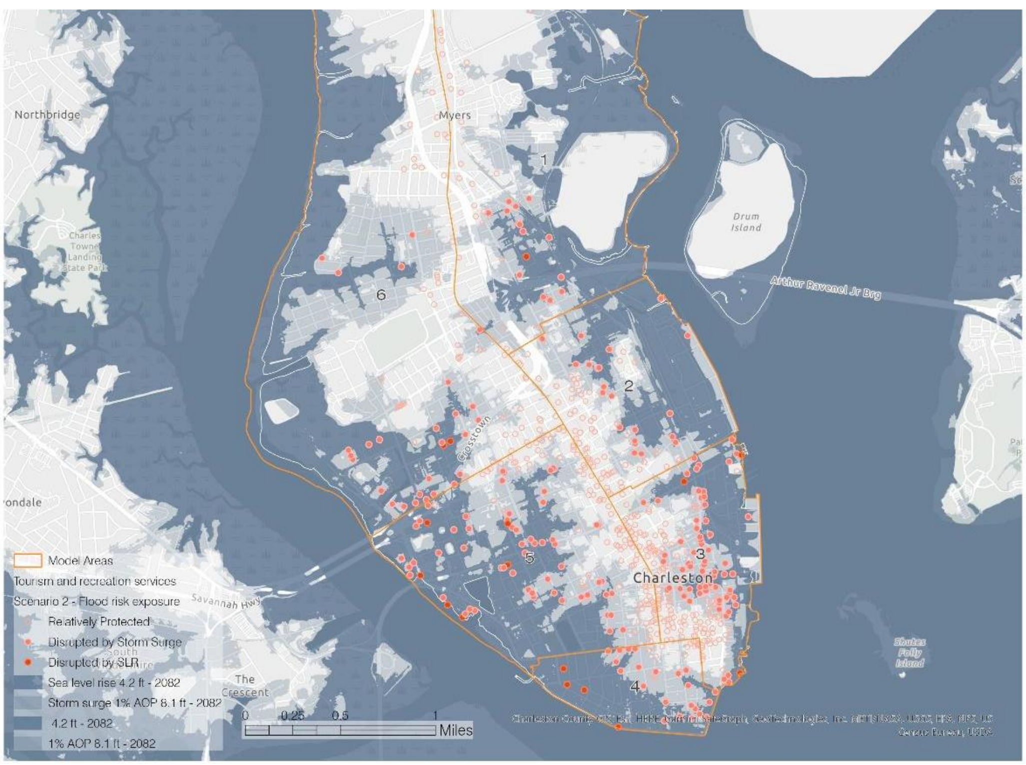


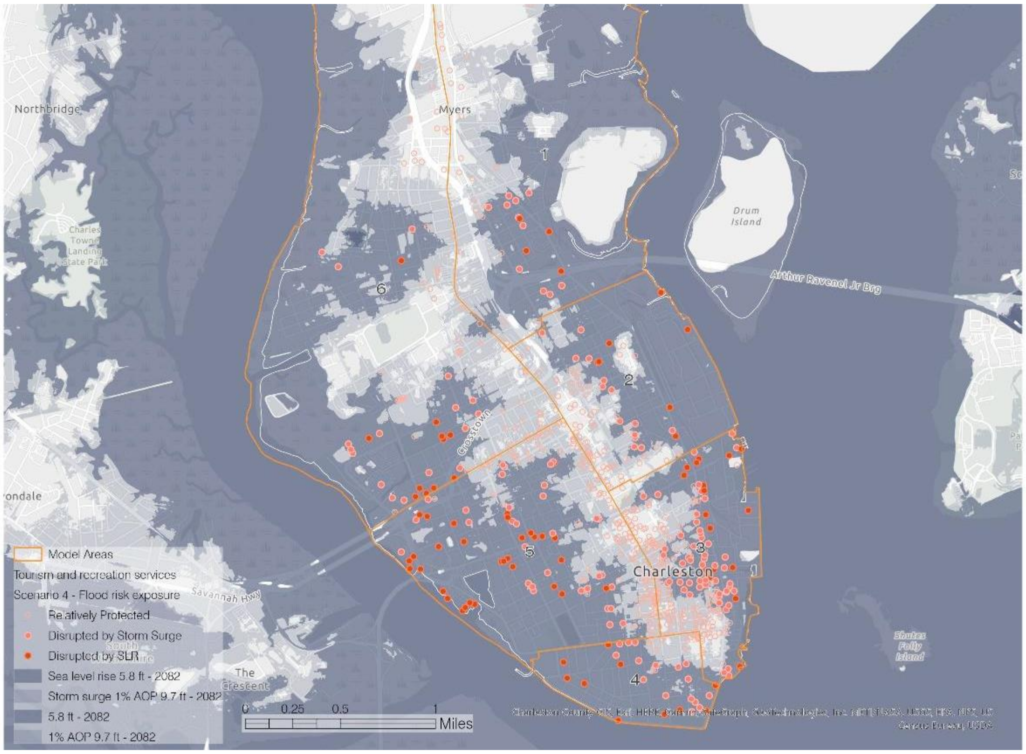
Figure 34. Climate Central Risk Finder, Kopp et al., 2017

The topobathymetric data exported in the Grasshopper model structured the first module – "Flood Impact Assessment". I analyzed slopes, extracted the contours for the illustrative clarity of the terrain conditions, and classified the terrain by depths. The Continuously Updated Digital Elevation Model (CUDEM) provided better representation of the terrain for both land and underwater which we need in this model. NCEI Continuously Updated DEM (CUDEM) data includes NCEI-stewarded bathymetry and topography mosaic DEMs. The depth values in meters, stored as 32-bit floating point values. The rasters are fine grain with cell sizes range from 1/9 arcsecond to 3 arcseconds, allowing the essential accuracy of building level elevations (see Figures 35-37).

Figure 35. Short-term scenarios of SLR and coastal storm surge with the tourism/recreation businesses affected, 2032



Figures 36-37. Long-term scenarios of SLR and coastal storm surge with the tourism/recreation businesses affected, 2082, RCP`s 4.5 (top) and 8.5 (bottom).

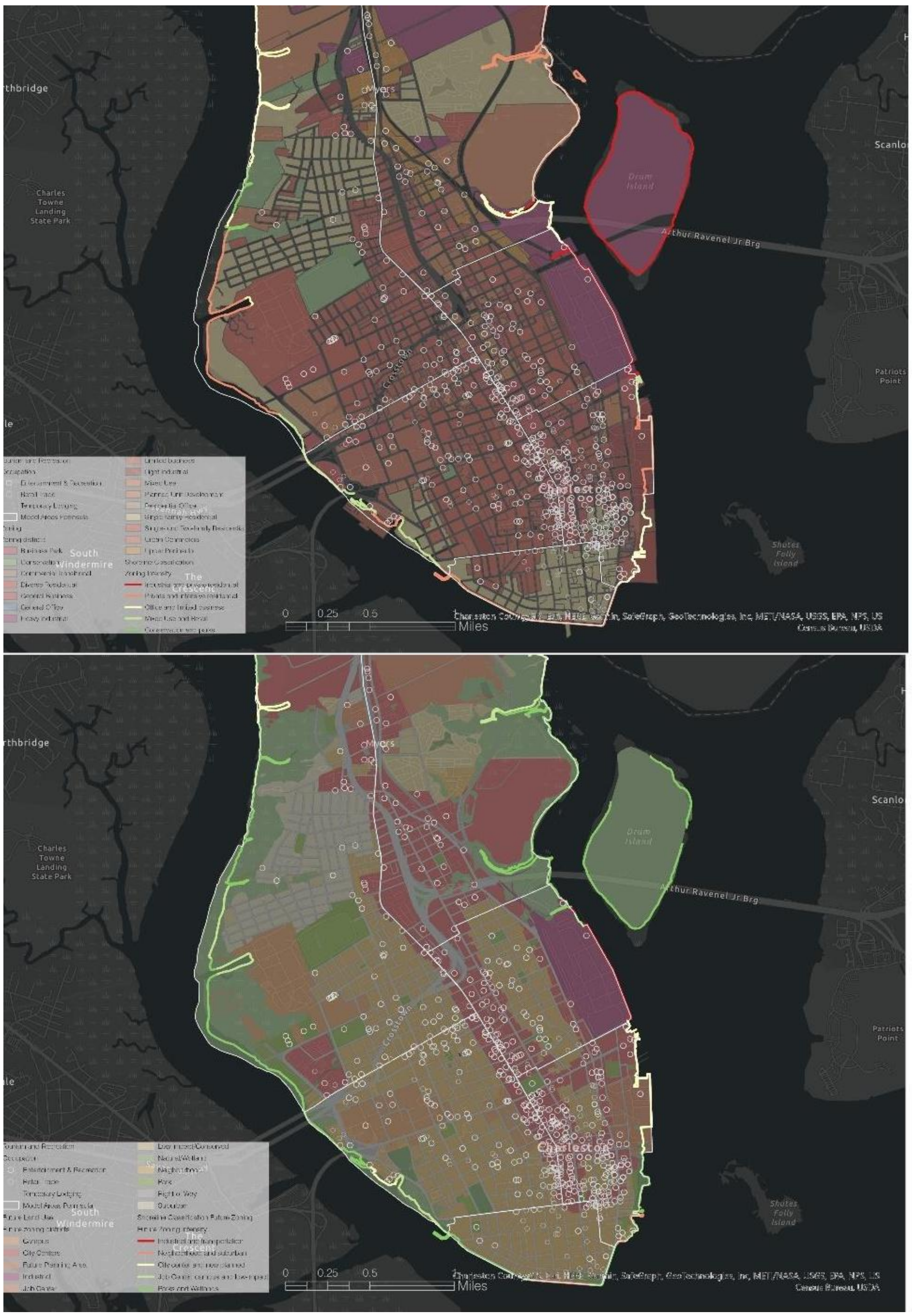

Northbridge
Myers
Drum Island
Arthur Ravenel Jr Brg
Crosstown
Charleston
Savannah Hwy
The Crescent
Model Areas
Tourism and recreation services
Scenario 4 - Flood risk exposure
Relatively Protected
Disrupted by Storm Surge
Disrupted by SLR
Sea level rise 5.8 ft - 2082
Storm surge 1% AOP 9.7 ft - 2082
5.8 ft - 2082
1% AOP 9.7 ft - 2082
0 0.25 0.5 1 Miles

Appendix 02.

Living Shorelines Suitability

The featured suitability parameters are represented by the shapefiles of secondary GIS data: Shoreline perimeter structure, Topobathymetry slope, Wetland types, Shoreline transformation index, Exposure to the maximum fetch energies, and Zoning patterns. Each of the parameters are ranked from 1 to 5 representing the values gradient from the least suitable to the most suitable for the NbS sitting. The resulting NbS suitability ranking is calculated as an average 1 to 5 value of the six variables discussed: NbS_Rank=(!Str_Rank! + !Slope_Rank! + 2 * !Wetland_Rank! + 3 * !Zoning_Suitability! + !Energy_Rank! + 3 * !SCR_R!) /10. In my model I weighed parameters of structural characteristics of the shoreline segments based on their importance for the ecosystem's vitality according to the literature review. As such, according to the study on the Economics of Climate Adaptation (Reguero et al., 2014), urbanization affects the risks for ecosystems greater than the natural context, and I weigh zoning with the coefficient of 0.3. The importance of shoreline change is also ranked with 0.3, and the current wetlands conditions as 0.2. The remaining parameters were equally weighed as 0.1 of the total. Nevertheless, these parameters might be updated in ArcGIS equation based on the local conditions and should be further defined based on the updated research. I explained their components per suitability factor in detail below.

The NbS strategy proposed with “Imagine the wall” study subdivided the perimeter in the areas of various solutions based on the urban context. In my study land use patterns vary from the most suitable to ecosystems to the least suitable. Intensive and low-accessible green interventions are assigned the rank of 1 – industrial zones and private residential areas. The most suitable for the ecosystem restoration are recreation, conservation, and park uses – corresponding with the rank of 5. Since I subdivided the area of interest into the model areas based on the land use, I can further refer to this parameter when assigning the simplified solution to the model areas perimeter. The land use factors of the shoreline suitability ranking are illustrated in the Figures 38-39.



Figures 38-39. Shoreline suitability ranking "Land use" and "Future land use" components (Charleston GIS services, 2022)

Ecosystem context

The NOAA Environmental sensitivity index shoreline data is classified based on wave exposure as it relates to coastal storm risk measures. The SACS utilized the NOAA Environmental Sensitivity Shoreline Index data for a consistent shoreline dataset across the study area for the primary use of oil spill contingency planning (NOAA 2017, NOAA 2000). The structure of shorelines defined by SACS South Atlantic study by USACE shows the ecosystem and man-made structures of the shore (https://data-sacs.opendata.arcgis.com/apps/f0d3616a44824897a1bfbd1a6f1ce063/explore). The values from 1 to 5 correspond with hard structures exposed to the winds and waves to wetlands/ marshes/ swamps sheltered from them (See Figure 40)

Figure 40. Shoreline suitability ranking "Existing Structure" component - (USACE, ESI, 2021)

The databases of the National Wetland Inventory NWI provide the habitat layers defining the rank of wetlands suitability of a shoreline segment (FWS, 2020). It is based on visible hydrologic vegetation, which means the importance of incorporating marine and estuarine aquatic vegetation on the further stages upon data availability. The distribution of coastal wetlands around the Charleston Peninsula with the corresponding types allow to rank the areas. The deepwater wetlands do not provide coastal flood protection, whereas the estuarine and marine wetlands provide the opportunity to restore the protective ecosystems (See Figure 41).

Figure 41. Shoreline suitability ranking "Wetlands allocation" component - (FWS, 2020)

Topobathymetric context

Ecosystem restoration and ecosystem-based solutions require a range of topographic gradients to support diverse vegetation communities and provide ecosystem services. Thus, topobathymetric structure of the area is classified into slopes below 3 %, 3-5%, 5-10%, 10-20%, and over 20 %. According to the NNBF guidelines these parameters correspond with the green-gray specter of possible ecosystem-based solutions (Bridges et al., 2021 b). Charleston has a relatively gentle slope with most areas suitable for an array of ecosystem-based solutions. Nevertheless, this parameter will have more substantial importance in the areas of steeper terrain (See Figure 42).

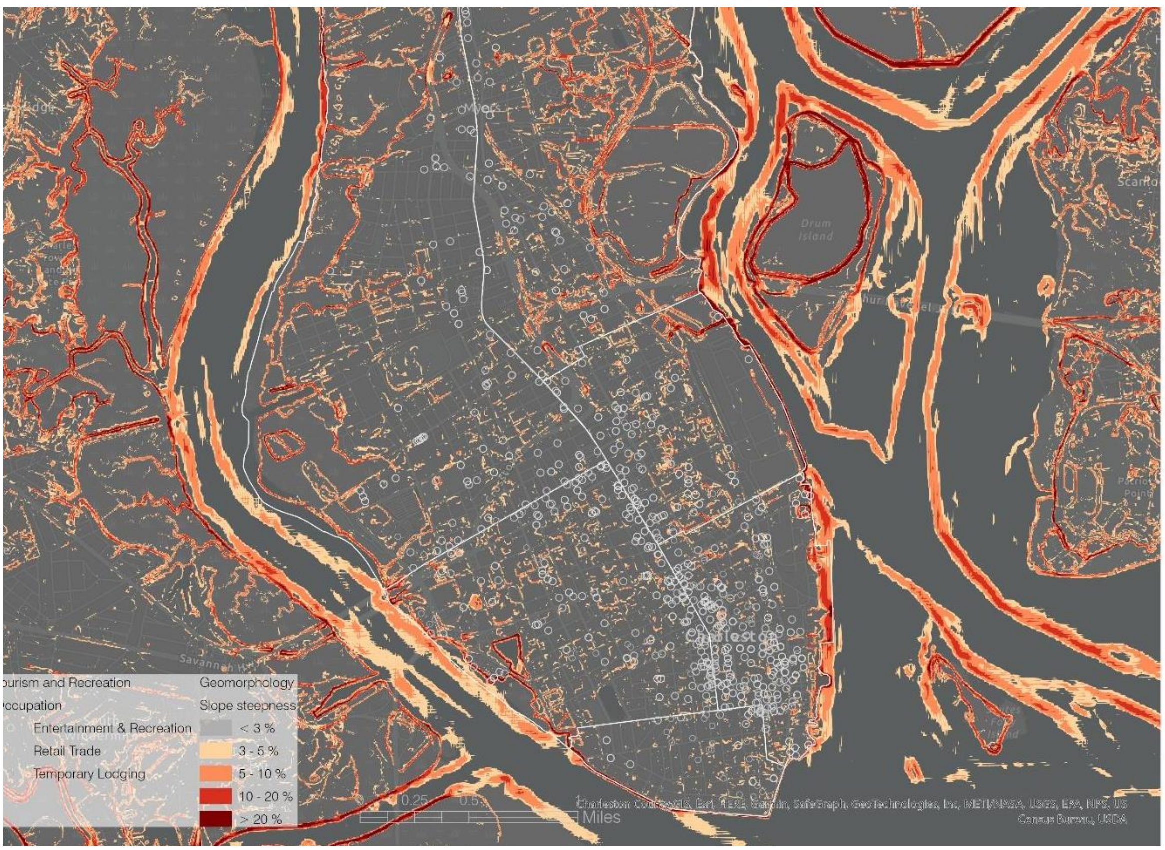


Figure 42. Shoreline suitability ranking "Topobathymetry" component - (NOAA Digital coast, 2021)

Furthermore, ecosystem vegetation requires sediment accumulation to compensate for compaction, decomposition, and erosion of the seabed surface (Morris et al. 2016). Thus, we aim to assess sediment supply, accretion, erosion, and distribution of the sedimentation. Sediment supply is critical for the development and maintenance of wetlands, as it provides the substrate for vegetation growth and nutrient cycling. In this study I used the available layers of South Carolina Living Shoreline Explorer (TNC, 2020, https://maps.coastalresilience.org/southcarolina/living-shorelines/). The application classifies shoreline change rates associated with the wind and wave conditions. The estuarine shoreline transects are examined by associated change rates based on South Carolina Department of Health and Environmental Control's Office of Ocean and Coastal Resource Management (DHEC OCRM) using the open-source geospatial tool, AMBUR (Analyzing Moving Boundaries Using R). The analysis utilized three time steps: 1800s, 1930s, and 2000s, covering a period from 1849 to 2015. The tool also considers the averaged fetch as a factor in wind wave energy, but also establishes a threshold for estuarine shorelines. This threshold represents the maximum energy that could be introduced by specific storm events when conditions and wind direction align for maximum impact. Sites with a maximum fetch distance less than 2.75 miles in any direction are classified as having low energy potential, while sites with a maximum fetch distance exceeding 6 miles in any direction are classified as high energy potential. These distances are equivalent to a RWE20 of 200 J/m and 700 J/m, respectively (See Figure 43).

Local inlets, channels, creeks, and estuaries transfer volumes of water and sediments twice a day. For detailed estimation of these patterns the numeric modeling and observation-based data will be needed. Future climate and sea-level rise projections can also influence the sediment transport patterns and the effectiveness of nature-based solutions. Incorporating these projections into the assessment can help ensure that the solutions are designed to be resilient and adaptable to changing conditions. (Bouw, 2021)

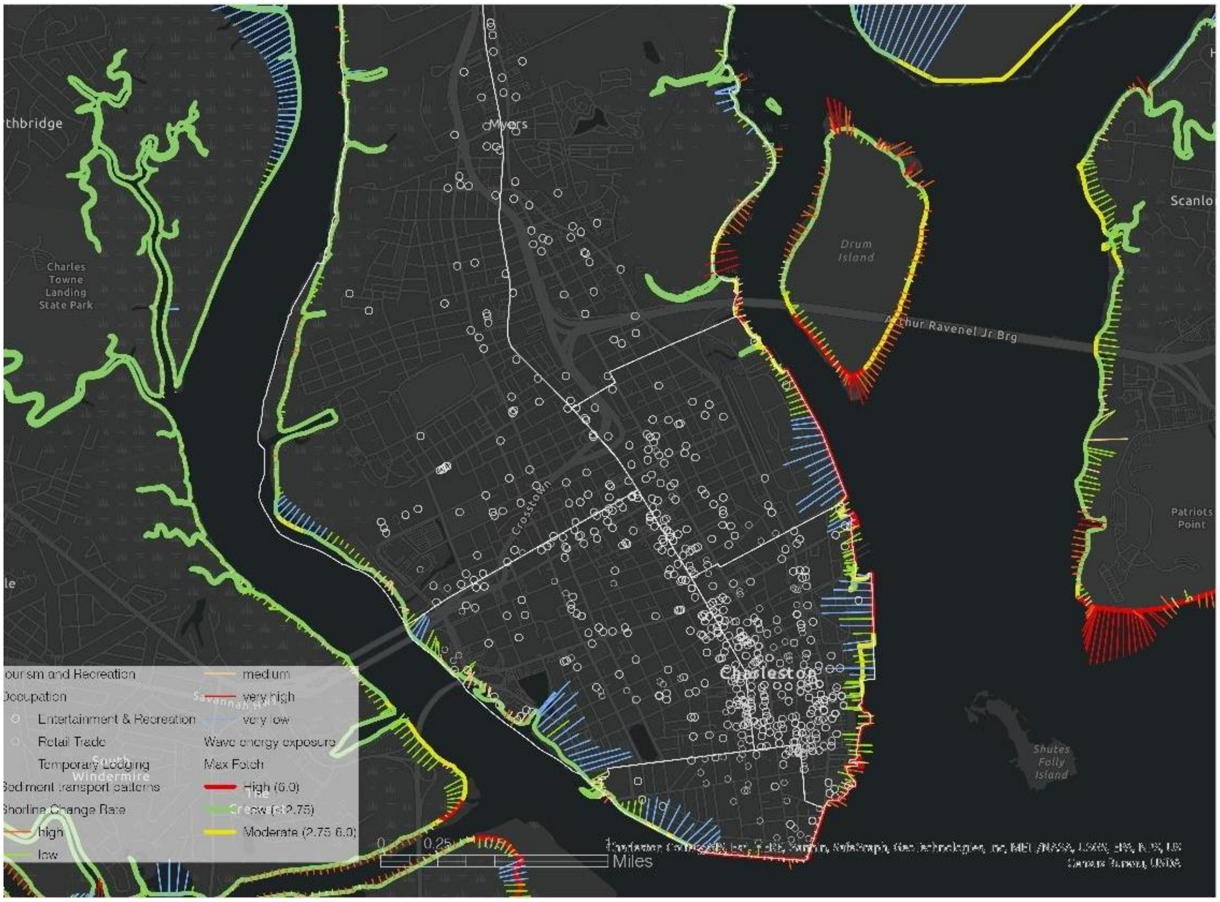


Figure 43. Shoreline suitability ranking "Wave energy" and "Sediment patterns" components (TNC, 2020)

Appendix 03.

Nature-based solutions

Basic principles of NbS performance

The meta-analyses of sixty-nine studies conducted by Narayan et al.(2017) has shown how various habitats reduce wave heights depending on the site conditions - between 35% and 71%. For instance this study shows that wetlands reduce them by 72% (95%CI: 62–79%). For the harder solutions, flood protection is mainly defined by width relative to the wave height and height (see Figure 44). The study of Barbier et al., 2013 analyzes the transects of wetlands to define their protective values. He defines the flood mitigation capacities by wetlands width and roughness (see Table 15).

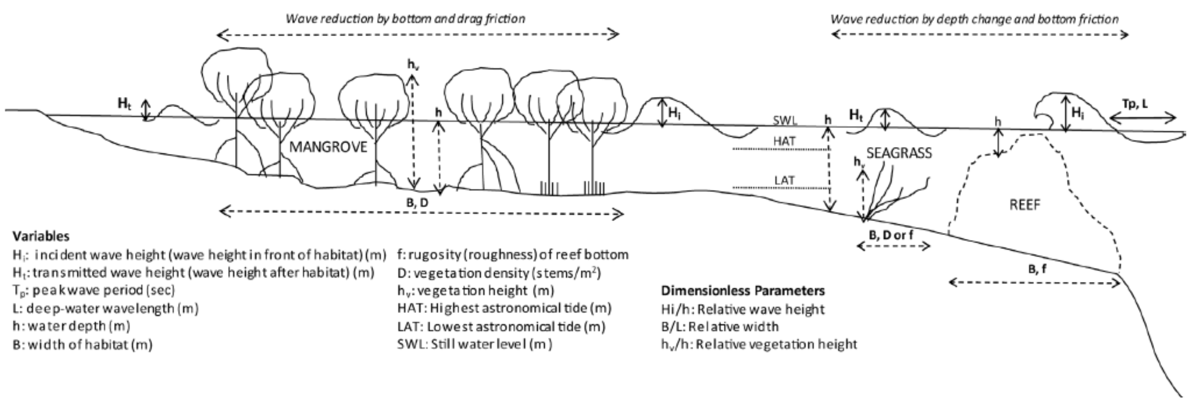


Figure 44. Narayan et al., 2017. Wave high reduction provided by various ecosystems

Estimated wetland impacts on attenuating maximum storm surge levels (S)		Estimated marginal values of wetlands in terms of avoiding damages to residential property	
	Change in storm surge		**Marginal value**
1% change in W_L per segment	−8.4% to −11.2%	0.1 increase in W_L per m	\$99.29 to \$132.87
1% change in W_R per segment	−15.4% to −28.1%	0.001 increase in W_R per m	\$23.72 to \$43.24
9.4 to 12.6 km change in W_A	−1 m	0.1 increase in W_L per segment	\$591,886 to \$792,082
		0.001 increase in W_R per segment	\$141,399 to \$257,762

W_L is represented by the wetland/water ratio ranging from open water ($W_L = 0$) to solid marsh ($W_L = 1$).
W_R is represented by Manning's n for bottom friction caused by degree of wetland vegetation ranging from no vegetation ($W_R = 0.02$) to high density vegetation ($W_R = 0.045$).
Mean maximum surge level (S) is 2.302 m.
Mean wetland/water ratio (W_L) is 0.408.
Mean Manning's n (W_R) is 0.032.
Mean transect segment length (x) is 5,961 m.
Based on Tables S1–S3.
doi:10.1371/journal.pone.0058715.t001

Table 15. Wetlands wave attenuation capacity (Barbier et al., 2013)

More specifically, studies show the performance of different ecosystem-based solutions are explored and explained in the studies of Guerry et al. (2022) and the International Guidelines for NNBF (Bridges et al., 2021). These are shown in the Figure 46 and explained in detail by a Nature-based solution below

Adaptation Measure	Definition	Landscape configuration, design, & process guidelines
Nearshore reefs[1] 	Nearshore (lower intertidal/subtidal) reefs made of structures such as bags of oyster shell and reef balls made of baycrete (a cement mixture composed mostly of Bay sand and shells) that provide hard substrate for shellfish including native Olympia oysters (*Ostrea lurida*) and other aquatic plants and animals. Nearshore reefs can reduce wave transmission at lower tidal elevations and stabilize areas in their lee (Latta and Boyer 2015).	Best suited to shallow water in areas of low wave action, at the low end of mudflats. They generally need to be located relatively close to shore in order to create a wave shadow in their lee, trapping sediment and reducing marsh edge erosion. Areas with relatively low salinity and relatively high turbidity are less suitable for supporting native oysters than areas with higher salinity and lower turbidity (Subtidal Goals 2010).
Submerged aquatic vegetation[2] 	Submerged aquatic vegetation (SAV) refers to all underwater flowering plants. Eelgrass (*Zostera marina*) is the main species in the lower parts of the San Francisco Estuary, but other submerged vegetation species exist throughout the Bay as well. SAV can contribute to trapping sediment and slowing shoreline erosion.	Salinity and light are limiting factors for eelgrass beds. Eelgrass can grow in sand, silt, or clays, and do best where current speeds and wave energy are not excessive. Potential exists to establish eelgrass beds at depths less than about 2 m in broad swaths along the shores of San Pablo Bay, Central Bay, and South Bay (Merkel 2005).
Coarse beaches[3] 	Coarse or composite estuarine beaches are dynamic features that can consist of a mixture of sand, shell, gravel, or cobble. Coarser gravel and cobble beaches can dissipate wave energy over shorter distances and therefore may be more suitable within an urbanized and constrained estuary.	Beaches dissipate and reflect wave energy. They can be placed in front of levees, roads, or other infrastructure vulnerable to wave overtopping, or in front of marshes vulnerable to erosion. Groins or other retention structures should be considered for beaches implemented along shorelines where the dominant waves transport sediment down the shoreline (i.e., high drift), but aren't necessary for naturally constrained areas (e.g., between headlands).
Tidal marsh[4] 	Protecting, maintaining, and restoring tidal marshes and their associated tidal flats is critical for sustaining their flood risk management services (Goals Project 2015). Specific actions include: restoring tidal action to diked Baylands to restore marshes, planting native species to accelerate colonization, placing sediment to raise subsided areas, and creating higher areas within marshes to provide high-tide refuge. In existing marshes sediment placement can help maintain marsh elevation with sea-level rise.	The topography of the marsh and its associated mudflat plays a significant role in wave refraction, shoaling, and breaking. Marsh width is one important factor that influences the degree to which a tidal marsh is able to attenuate waves. Vegetation type, elevation within the tidal frame, and salinity levels are important considerations when designing marshes for sea level rise adaptation.
Ecotone levees[5] 	Ecotone levees are gentle slopes or ramps (with a length to height ratio of 20:1 or gentler) bayward of flood risk management levees and landward of a tidal marsh. They stretch from the levee crest to the marsh surface and can provide wetland-upland transition zone habitat when properly vegetated with native clonal grasses, rushes, and sedges (Nur et al. 2018). They can attenuate waves, provide high-tide refuge for marsh wildlife, and allow room for marshes to migrate upslope with sea level rise.	Slopes are designed to stretch down from the crest of the flood risk management levee to tidal marsh elevation with a gradient between 20:1 and 30:1. Subsurface irrigation on the ecotone levee (i.e., a "horizontal levee") can be incorporated to support fresh to brackish wetlands on the levee at the upland edge of the tidal marsh. Levees wider than 25 m, planted with dense vegetation between 50–100 cm tall, can provide measurable benefits to tidal marsh dependent birds, both in the short- and long-term.

Table 16. Parameters of the various ecosystem-based strategies (Guerry et al, 2022)

Barrier islands - living breakwaters

This type of green infrastructure provides a multi-faceted nature-based approach to wave energy protection by incorporating habitat and recreational features into the engineered structure seaward from a protected area. The basic principle of allocating this structure offshore provides the highest potential for wave reduction based on the dissipation (see Figure 45).

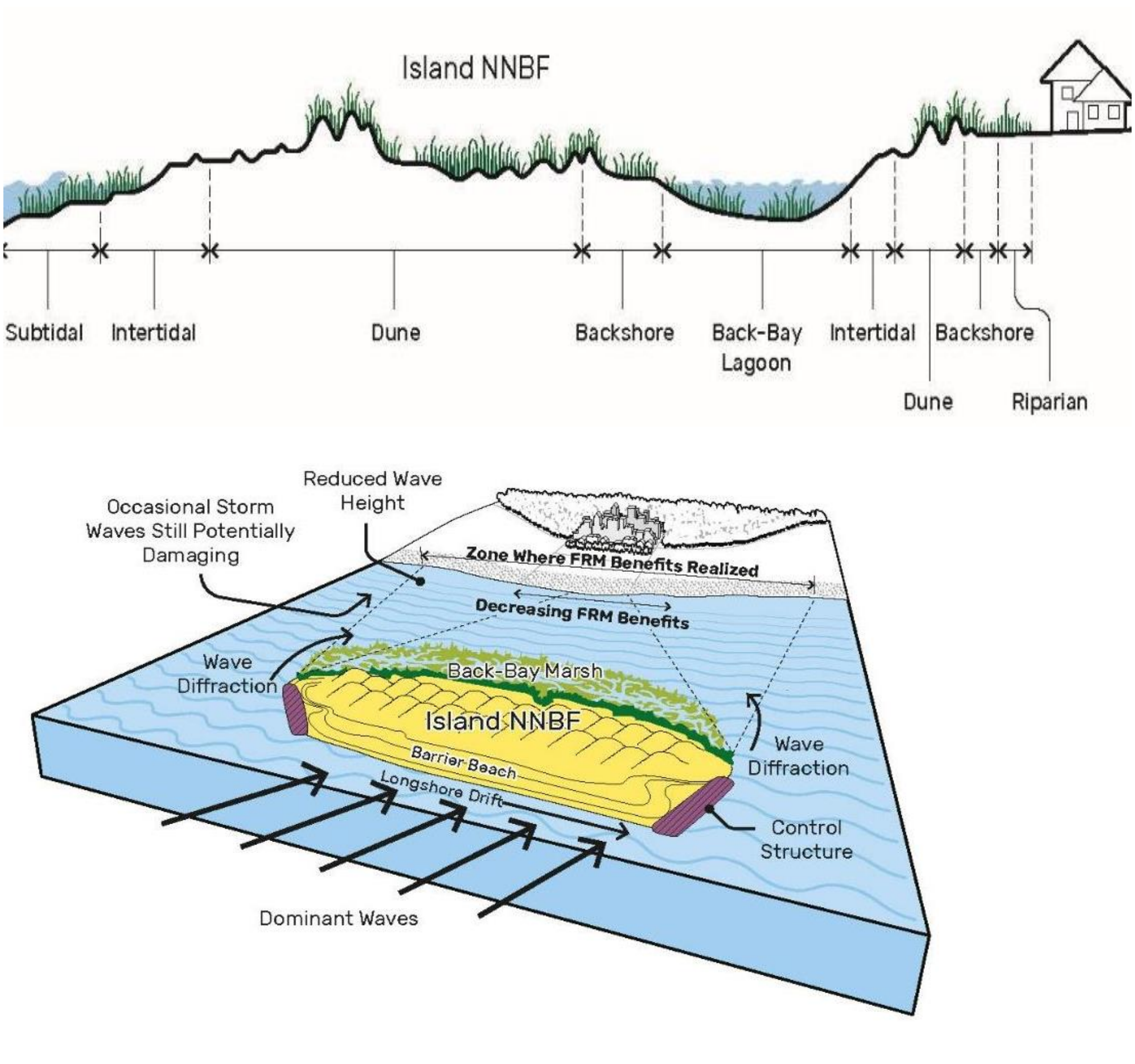


Figure 45. Barrier islands transect and protective principle (Bridges et al, 2021 b.)

Living bulkheads with softened edges (riprap, vegetated levee)

These solutions represent a half-structured wall with a softened interface suitable for oyster beds and other ecosystems within the rocky shores and rip-rap. The green parts of the structures dampen wave energy and provide additional resiliency to the coastline by enhancing aquatic habitat. The principle and the transect are illustrated with the Figure 48

Figure 46. Bulkheads with softened edge transect and protective principle (SCAPE, 2020)

Vegetated dikes and levees

These hybrid structures combine a hard moderately steep protective structure allowing the allocation of vegetation both inland and seaward. They can incorporate surface vegetation including shrubs with higher wave attenuation capacities (See Figure 49).

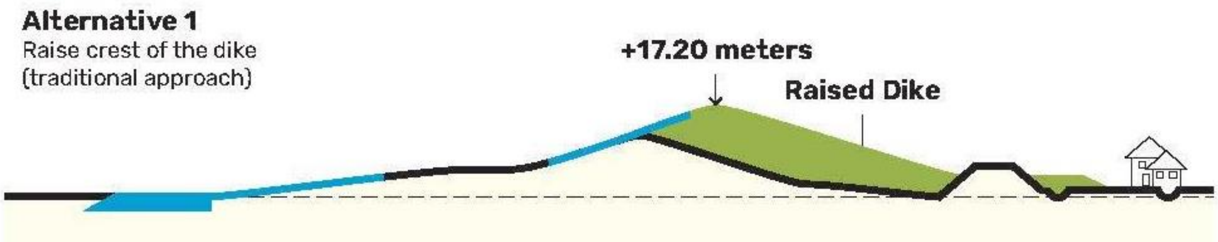


Figure 47. Vegetated dikes transect and protective principle (Bridges et al, 2021 b.)

Horizontal levee

This solution combines a hardened structure with an elongated slope toward the water. It absorbs wave energy and provides room for tidal wetlands to migrate upslope as seas rise. The solution has the top elevation allowing the reduction of the storm surge levels under short-term scenarios. It allows the integration of trails, connectors, greenways, parks, and other green infrastructure features and temporary outdoor activities (See Figure 50).

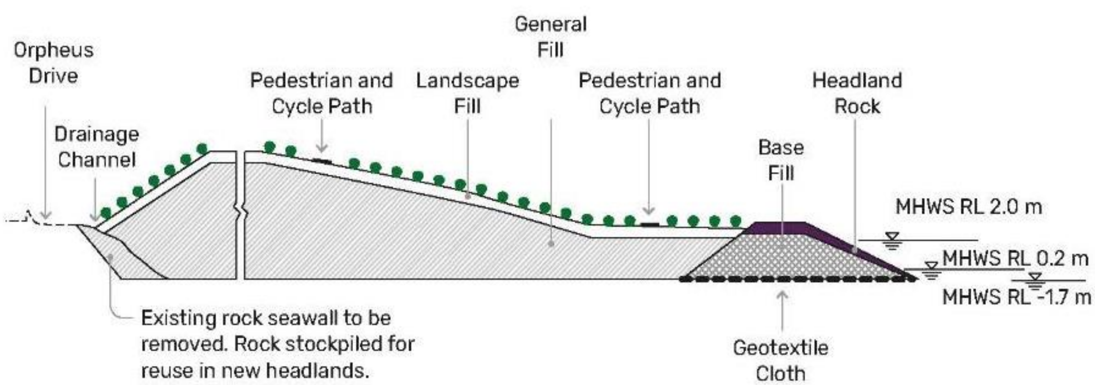


Figure 48. Horizontal levees transect and protective principle (Tonkin & Taylor, 2013)

Wetlands restoration

This is the most naturally based solution among the chosen range, and it requires especially flat slopes and low wave energies to allow the sustained development of the ecosystem. Wetlands need to have an additional source of sediments to adjust for the sea level rise. Therefore, it is essential to avoid hard structures between wetlands and shoreline thus allowing the mass accretion. A potential erosion preventing measure will be the structured toeing of the slope seaward. A 1% increase of the Wetland width along the segments is expected to reduce storm surge by 8.4% - 11.2%, whereas an 1% in wetland roughness - by 15.4% to 28.1%. In terms of storm surge depths – it means that 9.4 - 12.6 km of wetlands will reduce the storm surge by 3 ft (See Figure 51, Table 52).

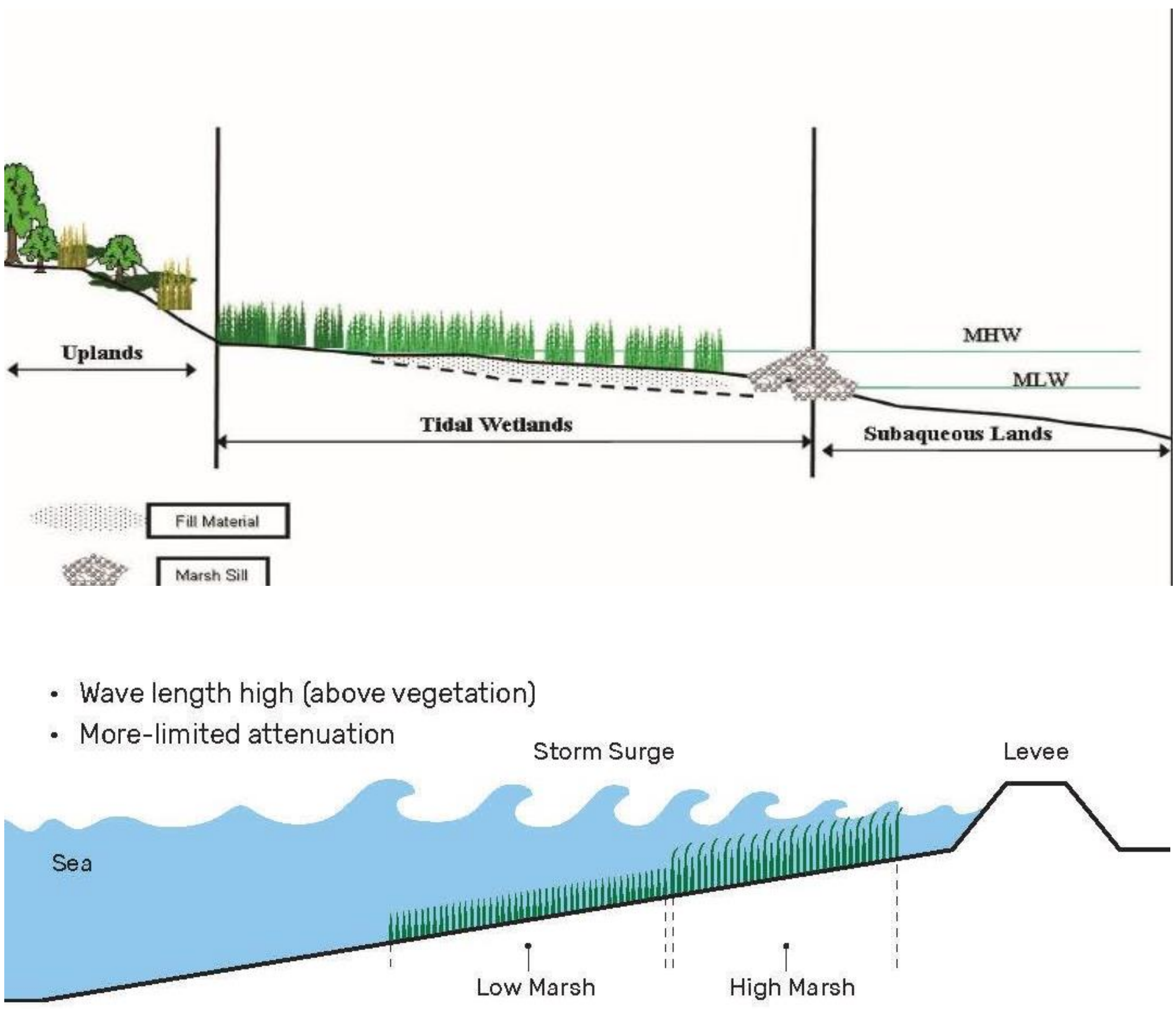


Figure 49. *Wave-attenuation function of wetlands (Bridges et al., 2021b.)*

Design parameter	Affected function	Performance factors and considerations	Performance guidelines
Wetland location	• Erosion protection • Accretion • Wave attenuation • Surge attenuation • Flood storage	• Location relative to assets • Position in estuary (e.g., close to mouth, inlets) • Exposure (e.g., fetch, proximity to navigation channels) • Proximity to structural measures (e.g., levees, bulkheads)	• Properties behind marshes and mangroves have lower flood damages than those with no wetlands (Narayan et al. 2017, 2019). • Proximity to and configuration of inlets and exposure to ocean surge are dominant factors affecting wetland surge-attenuation capacity (Lawler, Haddad, and Ferreira 2016). • Hardened structure design can lead to wave reflection and scour of wetland (Morton and Barras 2011).
Wetland shape and size	• Erosion protection • Wave attenuation • Surge attenuation • Flood storage	• Distance from shoreline to upland or structure • Size relative to estuary • Storage volume	• Greatest wave attenuation occurs in first tens of meters of wetland (Garzon et al. 2019; Bao 2011). • Typical surge-attenuation rates are a function of wetland size; typical surge-attenuation rates for marsh 1.7 to 25 cm/km (Leonardi et al. 2018) and mangroves 4.2 to 48 cm/km (Narayan et al. 2019) reported. • Storage volume should be 20% to 40% of total volume of estuarine reach to store significant floodwater (Stark et al. 2016).
Wetland elevation	• Accretion • Wave attenuation • Surge attenuation	• Elevation relative to tidal datum and tide range (upper intertidal range most conducive to primary productivity) • Elevation relative to protected assets and structural measures	• Greater elevation provides greater flood protection (Loder et al. 2009). • Platform elevation can be manipulated to create multiple wetland vegetation zones to provide FRM benefits at range of water levels (Horstman et al. 2015).
Structural elements	• Erosion protection • Accretion • Wave attenuation • Surge attenuation • Flood storage	• Structure type • Temporary or permanent • Structure location • Structure function	• Structures should only be used where necessary and should enhance wetland function. • Structures designed to prevent erosion should be sized appropriately to address erosion issues (Melby et al. 2005).
Sediment properties	• Erosion protection	• Bulk density, organic matter	• Low bulk density, higher organic matter, and lower percent sand are associated with lower erosion rates (also associated with well-developed marsh environments; Feagin et al. 2009).

Nearshore bathymetry	• Erosion protection • Accretion • Wave attenuation • Surge attenuation	• Bottom elevation adjacent to wetland • Bottom geometry adjacent to wetland	• Shallow tidal flats are associated with less wetland erosion and help dissipate wave energy (Bouma et al. 2016). • Wide mudflats may help supply sediment to wetland features during storms, allowing them to accrete vertically (Ganju 2019; Schuerch, Spencer, and Evans 2019).
Connectivity to other features	• Wave attenuation • Surge attenuation	• Distance to mudflat, transitional and upland plant communities • Slope between wetland and adjacent features	• Deep water adjacent to wetlands can exacerbate wetland edge erosion (Ganju 2019). • Levees that reduce wetland width can lead to amplified surge by reducing available flow area (Stark et al. 2016).
Tidal channels and open-water elements	• Erosion protection • Accretion • Wave attenuation • Surge attenuation • Flood storage	• Channel width, depth • Channel orientation • Marsh edge area ratio • Proportion of unvegetated to vegetated area	• Deeper and wider wetland channels allow surge and waves to propagate further into the wetland than do shallow, narrow channels (Stark et al. 2015, 2016; Lawler, Haddad, and Ferreira 2016). • Greater proportion of channels and ponds reduces wave- and surge-attenuation capacity (Barbier et al. 2013).
• Vegetation type • Height • Density • Diameter • Complexity • Flexibility • Roots	• Erosion protection • Accretion • Wave attenuation • Surge attenuation	• Height: typical height above wetland platform • Density (as a function of height): proportion of flow area blocked per unit area, number of vertical elements (i.e., stems) per unit area, leaf area index • Flexibility: qualitative description (flexible versus rigid), quantitative (modulus of elasticity, moment of inertia) • Roots: mass per unit volume of soil of live plant roots, depth above which 95% of live root mass occurs	• Height: taller vegetation provides greater resistance to flow and waves over a greater range of water levels (Beudin et al. 2017). • Density: greater vegetation density blocks more flow and exerts more friction than less dense vegetation (Loder et al. 2009); distribution of aboveground biomass affects velocity profile and scour potential (Horstman et al. 2015). • Flexibility: rigid vegetation provides greater attenuation benefits than flexible vegetation (Beudin et al. 2017) but may be more prone to breakage or uprooting, whereas flexible vegetation may lay prone and protect soil from scour (Vuik et al. 2019). • Roots: greater rooting depth and large density of roots will provide erosion resistance at greater depth along marsh edges (Howes et al. 2010; Silliman et al. 2019).

Table 17. Wetlands design and performance (Bridges et al., 2021b)

The model assumes that the choice of a transect is related to the most suitable parameters according to the previously discussed suitability module. The dimensions are chosen based on the height and slope inclination minimally required to prevent the permanent levels of SLR expected according to the planning scenarios, while partially attenuating storm surge. This is an effort to find the golden middle between planning the structures with considerable margins against the extreme risks, and avoiding preparation to protect the recreation qualities of the site.

Appendix 04.

Business operation module

The specific assessment equations used in the Hazus model to incorporate business operation losses include depth-damage and disruption functions. Depth Damage Function (DDF) curves allow to estimate structural damage repair times and further assess the disruption time (FEMA, 2009). I need solely retail and tourism services footprints within the study area, that are summed by sector and used to identify disruption costs. The Hazus model uses a loss function to compute the economic losses associated with business interruption can be represented with the following equation:

Economic Loss = Output x (1 - BIF) x R x (1 - OFR),

or “!(!Output_DB! * (1-!BIF!) * !Rec_time! * (1-!OFR!)) * !Disruption_Sc2_with!” in ArcGIS code

where:

Output = Annual output of the business - annual revenue generated by the business that we take from Hazus data, but either can be estimated based on local economic data

BIF = Business Interruption Factor - the degree of business interruption based on the sector and can be obtained from the Hazus database or can be customized based on local data.

R = Recovery Time - time required to restore the business to pre-disaster conditions defined by Hazus multipliers or local inputs

OFR = Output Failure Rate - the extent to which the business is able to recover its output after the disaster and can be estimated based on local data

I estimated the resulting variables using the Grasshopper interface per an economic sector of interest (RES4, COM1, COM8) aggregated by model area to represent the potential economic losses of operations and their prevention across the scenarios. The model calculated the output loss by multiplying the impacted services footage times recovery time in months times service interruption multiplier times average annual output loss per day per square foot. The tables below provide the explicit model outputs for model areas over the planning scenarios. In the Figures 18 – 20 the levels of the flood risk exposures are illustrated and compared for “with” and “without project” situations.

Model Areas	Occupation	Nn protected	Ratio protected	Nn affected	Ratio affected	Nn exit	Ratio exit	Nn services	Tourism/ Other	Density services	Nn exposed	Exposed/ Protected
MA 1	Other	191	96.95%	6	3.05%	0	0.00%	197		0.14	6	3.05%
	Retail	27	93.10%	2	6.90%	0	0.00%	29		0.02	2	6.90%
	Entertainment	21	100.00%	0	0.00%	0	0.00%	21		0.01	0	0.00%
	Subtotal tourism	**48**	**96.00%**	**2**	**4.00%**	**0**	**0.00%**	**50**	**20.24%**	**0.04**	**2**	**4.00%**
		239	**96.76%**	**8**	**3.24%**	**0**	**0.00%**	**247**	**50**	**0.17**	**8**	**3.24%**
MA 2	Other	141	94.00%	9	6.00%	0	0.00%	150		0.30	9	6.00%
	Retail	38	100.00%	0	0.00%	0	0.00%	38		0.08	0	0.00%
	Entertainment	47	97.92%	1	2.08%	0	0.00%	48		0.10	1	2.08%
	Lodging	7	100.00%	0	0.00%	0	0.00%	7		0.01	0	0.00%
	Subtotal tourism	**92**	**98.92%**	**1**	**1.08%**	**0**	**0.00%**	**93**	**38.27%**	**0.19**	**1**	**1.08%**
		233	**95.88%**	**10**	**4.12%**	**0**	**0.00%**	**243**	**93**	**0.49**	**10**	**4.12%**
MA 3	Other	379	94.51%	22	5.49%	0	0.00%	401		1.01	22	5.49%
	Retail	106	96.36%	4	3.64%	0	0.00%	110		0.28	4	3.64%
	Entertainment	102	94.44%	6	5.56%	0	0.00%	108		0.27	6	5.56%
	Lodging	51	98.08%	1	1.92%	0	0.00%	52		0.13	1	1.92%
	Subtotal tourism	**259**	**95.93%**	**11**	**4.07%**	**0**	**0.00%**	**270**	**40.24%**	**0.68**	**11**	**4.07%**
		638	**95.08%**	**33**	**4.92%**	**0**	**0.00%**	**671**	**270**	**1.69**	**33**	**4.92%**
MA 4	Other	40	85.11%	7	14.89%	0	0.00%	47		0.21	7	14.89%
	Retail	9	81.82%	2	18.18%	0	0.00%	11		0.05	2	18.18%
	Entertainment	6	75.00%	2	25.00%	0	0.00%	8		0.04	2	25.00%
	Lodging	22	88.00%	3	12.00%	0	0.00%	25		0.11	3	12.00%
	Subtotal tourism	**37**	**84.09%**	**7**	**15.91%**	**0**	**0.00%**	**44**	**48.35%**	**0.20**	**7**	**15.91%**
		77	**84.62%**	**14**	**15.38%**	**0**	**0.00%**	**91**	**44**	**0.41**	**14**	**15.38%**
MA 5	Other	345	83.94%	66	16.06%	0	0.00%	411		0.56	66	16.06%
	Retail	83	91.21%	8	8.79%	0	0.00%	91		0.12	8	8.79%
	Entertainment	72	88.89%	9	11.11%	0	0.00%	81		0.11	9	11.11%
	Lodging	20	90.91%	2	9.09%	0	0.00%	22		0.03	2	9.09%
	Subtotal tourism	**175**	**90.21%**	**19**	**9.79%**	**0**	**0.00%**	**194**	**32.07%**	**0.27**	**19**	**9.79%**
		520	**85.95%**	**85**	**14.05%**	**0**	**0.00%**	**605**	**194**	**0.83**	**85**	**14.05%**
MA 6	Other	250	96.90%	8	3.10%	0	0.00%	258		0.13	8	3.10%
	Retail	39	95.12%	2	4.88%	0	0.00%	41		0.02	2	4.88%
	Entertainment	37	90.24%	4	9.76%	0	0.00%	41		0.02	4	9.76%
	Lodging	3	100.00%	0	0.00%	0	0.00%	3		0.00	0	0.00%
	Subtotal tourism	**79**	**92.94%**	**6**	**7.06%**	**0**	**0.00%**	**85**	**24.78%**	**0.04**	**6**	**7.06%**
		329	**95.92%**	**14**	**4.08%**	**0**	**0.00%**	**343**	**85**	**0.17**	**14**	**4.08%**
Total		**2036**	**92.37%**	**164**	**7.63%**	**0**	**0.00%**	**2200**	**736**	**0.63**	**164**	**7.63%**

Table 18. Tourism sector exposure to SLR and Storm Surge in a short term: Scenarios 1 and 3

Model Areas	Occupation	Nn protected	Ratio protected	Nn affected	Ratio affected	Nn exit	Ratio exit	Nn services	Tourism/ Other	Density services	Nn exposed	Exposed/ Protected
MA 1	Other	122	61.93%	70	35.53%	5	2.54%	197		0.14	75	38.07%
	Retail	21	72.41%	7	24.14%	1	3.45%	29		0.02	8	27.59%
	Entertainment	14	66.67%	7	33.33%	0	0.00%	21		0.01	7	33.33%
	Subtotal tourism	**35**	**70.00%**	**14**	**28.00%**	**1**	**2.00%**	**50**	**20.24%**	**0.04**	**15**	**30.00%**
		157	**63.56%**	**84**	**34.01%**	**6**	**2.43%**	**247**	**50**	**0.17**	**90**	**36.44%**
MA 2	Other	105	70.00%	43	28.67%	2	1.33%	150		0.30	45	30.00%
	Retail	31	81.58%	7	18.42%	0	0.00%	38		0.08	7	18.42%
	Entertainment	34	70.83%	14	29.17%	0	0.00%	48		0.10	14	29.17%
	Lodging	7	100.00%	0	0.00%	0	0.00%	7		0.01	0	0.00%
	Subtotal tourism	**72**	**77.42%**	**21**	**22.58%**	**0**	**0.00%**	**93**	**38.27%**	**0.19**	**21**	**22.58%**
		177	**72.84%**	**64**	**26.34%**	**2**	**0.82%**	**243**	**93**	**0.49**	**66**	**27.16%**
MA 3	Other	218	54.36%	181	45.14%	2	0.50%	401		1.01	183	45.64%
	Retail	76	69.09%	33	30.00%	1	0.91%	110		0.28	34	30.91%
	Entertainment	63	58.33%	43	39.81%	2	1.85%	108		0.27	45	41.67%
	Lodging	28	53.85%	24	46.15%	0	0.00%	52		0.13	24	46.15%
	Subtotal tourism	**167**	**61.85%**	**100**	**37.04%**	**3**	**1.11%**	**270**	**40.24%**	**0.68**	**103**	**38.15%**
		385	**57.38%**	**281**	**41.88%**	**5**	**0.75%**	**671**	**270**	**1.69**	**286**	**42.62%**
MA 4	Other	28	59.57%	17	36.17%	2	4.26%	47		0.21	19	40.43%
	Retail	7	63.64%	2	18.18%	2	18.18%	11		0.05	4	36.36%
	Entertainment	3	37.50%	3	37.50%	2	25.00%	8		0.04	5	62.50%
	Lodging	7	28.00%	18	72.00%	0	0.00%	25		0.11	18	72.00%
	Subtotal tourism	**17**	**38.64%**	**23**	**52.27%**	**4**	**9.09%**	**44**	**48.35%**	**0.20**	**27**	**61.36%**
		45	**49.45%**	**40**	**43.96%**	**6**	**6.59%**	**91**	**44**	**0.41**	**46**	**50.55%**
MA 5	Other	228	55.47%	172	41.85%	11	2.68%	411		0.56	183	44.53%
	Retail	66	72.53%	23	25.27%	2	2.20%	91		0.12	25	27.47%
	Entertainment	50	61.73%	27	33.33%	4	4.94%	81		0.11	31	38.27%
	Lodging	11	50.00%	10	45.45%	1	4.55%	22		0.03	11	50.00%
	Subtotal tourism	**127**	**65.46%**	**60**	**30.93%**	**7**	**3.61%**	**194**	**32.07%**	**0.27**	**67.00**	**34.54%**
		355	**58.68%**	**232**	**38.35%**	**18**	**2.98%**	**605**	**194**	**0.83**	**250.00**	**41.32%**
MA 6	Other	207	80.23%	46	17.83%	5	1.94%	258		0.13	51	19.77%
	Retail	29	70.73%	10	24.39%	2	4.88%	41		0.02	12	29.27%
	Entertainment	25	60.98%	16	39.02%	0	0.00%	41		0.02	16	39.02%
	Lodging	1	33.33%	2	66.67%	0	0.00%	3		0.00	2	66.67%
	Subtotal tourism	**55**	**64.71%**	**28**	**32.94%**	**2**	**2.35%**	**85**	**24.78%**	**0.04**	**30**	**35.29%**
		262	**76.38%**	**74**	**21.57%**	**7**	**2.04%**	**343**	**85**	**0.17**	**81**	**23.62%**
Total		**1381**	**63.05%**	**775**	**34.35%**	**44**	**2.60%**	**2200**	**736**	**0.63**	**819**	**36.95%**

Table 19. Tourism sector exposure to SLR and Storm Surge in a short term: Scenario 2

Model Areas	Occupation	Nn protected	Ratio protected	Nn affected	Ratio affected	Nn exit	Ratio exit	Nn services	Tourism/ Other	Density services	Nn exposed services	Exposed/ Protected
MA 1	Other	103	52.28%	80	40.61%	14	7.11%	197		0.14	94	47.72%
	Retail	17	58.62%	9	31.03%	3	10.34%	29		0.02	12	41.38%
	Entertainment	14	66.67%	6	28.57%	1	4.76%	21		0.01	7	33.33%
	Subtotal tourism	**31**	**62.00%**	**15**	**30.00%**	**4**	**8.00%**	**50**	**20.24%**	**0.04**	**19**	**38.00%**
		134	**54.25%**	**95**	**38.46%**	**18**	**7.29%**	**247**	**50**	**0.17**	**113**	**45.75%**
MA 2	Other	92	61.33%	43	28.67%	15	10.00%	150		0.30	58	38.67%
	Retail	29	76.32%	5	13.16%	4	10.53%	38		0.08	9	23.68%
	Entertainment	33	68.75%	12	25.00%	3	6.25%	48		0.10	15	31.25%
	Lodging	6	85.71%	1	14.29%	0	0.00%	7		0.01	1	14.29%
	Subtotal tourism	**68**	**73.12%**	**18**	**19.35%**	**7**	**7.53%**	**93**	**38.27%**	**0.19**	**25**	**26.88%**
		160	**65.84%**	**61**	**25.10%**	**22**	**9.05%**	**243**	**93**	**0.49**	**83**	**34.16%**
MA 3	Other	173	43.14%	175	43.64%	53	13.22%	401		1.01	228	56.86%
	Retail	68	61.82%	31	28.18%	11	10.00%	110		0.28	42	38.18%
	Entertainment	51	47.22%	45	41.67%	12	11.11%	108		0.27	57	52.78%
	Lodging	21	40.38%	29	55.77%	2	3.85%	52		0.13	31	59.62%
	Subtotal tourism	**140**	**51.85%**	**105**	**38.89%**	**25**	**9.26%**	**270**	**40.24%**	**0.68**	**130**	**48.15%**
		313	**46.65%**	**280**	**41.73%**	**78**	**11.62%**	**671**	**270**	**1.69**	**358**	**53.35%**
MA 4	Other	22	46.81%	16	34.04%	9	19.15%	47		0.21	25	53.19%
	Retail	7	63.64%	1	9.09%	3	27.27%	11		0.05	4	36.36%
	Entertainment	3	37.50%	3	37.50%	2	25.00%	8		0.04	5	62.50%
	Lodging	5	20.00%	15	60.00%	5	20.00%	25		0.11	20	80.00%
	Subtotal tourism	**15**	**34.09%**	**19**	**43.18%**	**10**	**22.73%**	**44**	**48.35%**	**0.20**	**29**	**65.91%**
		37	**40.66%**	**35**	**38.46%**	**19**	**20.88%**	**91**	**44**	**0.41**	**54**	**59.34%**
MA 5	Other	191	46.47%	120	29.20%	100	24.33%	411		0.56	220	53.53%
	Retail	64	70.33%	12	13.19%	15	16.48%	91		0.12	27	29.67%
	Entertainment	47	58.02%	20	24.69%	14	17.28%	81		0.11	34	41.98%
	Lodging	7	31.82%	11	50.00%	4	18.18%	22		0.03	15	68.18%
	Subtotal tourism	**118**	**60.82%**	**43**	**22.16%**	**33**	**17.01%**	**194**	**32.07%**	**0.27**	**76**	**39.18%**
		309	**51.07%**	**163**	**26.94%**	**133**	**21.98%**	**605**	**194**	**0.83**	**296**	**48.93%**
MA 6	Other	178	68.99%	64	24.81%	16	6.20%	258		0.13	80	31.01%
	Retail	23	56.10%	14	34.15%	4	9.76%	41		0.02	18	43.90%
	Entertainment	18	43.90%	16	39.02%	7	17.07%	41		0.02	23	56.10%
	Lodging	0	0.00%	3	100.00%	0	0.00%	3		0.00	3	100.00%
	Subtotal tourism	**41**	**48.24%**	**33**	**38.82%**	**11**	**12.94%**	**85**	**24.78%**	**0.04**	**44**	**51.76%**
		219	**63.85%**	**97**	**28.28%**	**27**	**7.87%**	**343**	**85**	**0.17**	**124**	**36.15%**
Total		**1172**	**53.72%**	**731**	**33.16%**	**297**	**13.12%**	**2200**	**736**	**0.63**	**1028**	**46.28%**

Table 20. Tourism sector exposure to SLR and Storm Surge in a short term: Scenario 4

Model Areas	Occupancy Classes of interest	No Exposure	Exposure Sc 1-3	Operation Loss, $	Prevented Loss (Without-With)	Op Loss With, $	Loss mitigation
	Retail Trade	27	2	153,889	153,889	0	100.00%
1	Entertainment & Recreation	21	0	0	0	0	-
	Retail Trade	38	0	0	0	0	-
	Entertainment & Recreation	47	1	544,254	544,254	0	100.00%
2	Temporary Lodging	7	0	0	0	0	-
	Retail Trade	106	4	426,935	426,935	0	100.00%
	Entertainment & Recreation	102	6	2,454,442	2,454,442	0	100.00%
3	Temporary Lodging	51	1	1,777,930	1,777,930	0	100.00%
	Retail Trade	9	2	63,531	63,531	0	100.00%
	Entertainment & Recreation	6	2	2,060,759	2,060,759	0	100.00%
4	Temporary Lodging	22	3	248,904	248,904	0	100.00%
	Retail Trade	83	8	1,099,039	1,099,039	0	100.00%
	Entertainment & Recreation	72	9	4,548,900	4,548,900	0	100.00%
5	Temporary Lodging	20	2	93,805	93,805	0	100.00%
	Retail Trade	39	2	58,582	58,582	0	100.00%
	Entertainment & Recreation	37	4	1,515,522	1,515,522	0	100.00%
6	Temporary Lodging	3	0	0	0	0	-
Total retail		**302**	**18**	**1,801,976**	**1,801,976**	**0**	**100.00%**
Total entertainment		**285**	**22**	**11,123,877**	**11,123,877**	**0**	**100.00%**
Total Lodging		**103**	**6**	**2,120,639**	**2,120,639**	**0**	**100.00%**
Total EIA SS 1,3		690	46	15,046,492	15,046,492	0	100.00%

Model Areas	Occupancy Classes of interest	No Exposure	Exposure Sc 2	Exit Scenario 2	Disruption With	Operation Loss Without, $	Operation Loss Exit, $	Prevented Loss (Without-With), $	Op Loss With, $	Loss mitigation
	Retail Trade	21	1	7	0	1,689,928	11,363,241	13,053,169	0	100.00%
1	Entertainment & Recreation	14	7	0	0	6,069,884	0	6,069,884	0	100.00%
	Retail Trade	31	7	0	0	4,441,573	0	4,441,573	0	100.00%
	Entertainment & Recreation	34	14	0	1	8,674,673	0	8,130,419	544,254	93.73%
2	Temporary Lodging	7	0	0	0	0	0	0	0	-
	Retail Trade	76	33	1	0	10,197,998	11,871,874	22,069,872	0	100.00%
	Entertainment & Recreation	63	43	2	2	74,804,935	86,186,348	160,129,420	861,863	99.46%
3	Temporary Lodging	28	24	0	0	11,364,124	0	11,364,124	0	100.00%
	Retail Trade	7	2	2	0	214,885	6,353,037	6,567,922	0	100.00%
	Entertainment & Recreation	3	3	2	0	2,271,321	206,075,839	208,347,160	0	100.00%
4	Temporary Lodging	7	18	0	0	1,803,433	0	1,803,433	0	100.00%
	Retail Trade	66	23	2	0	5,014,490	11,504,665	16,519,155	0	100.00%
	Entertainment & Recreation	50	27	4	0	21,560,993	159,359,511	180,920,504	0	100.00%
5	Temporary Lodging	11	10	1	0	4,215,597	6,840,590	11,056,187	0	100.00%
	Retail Trade	29	10	2	0	1,434,996	5,858,176	7,293,172	0	100.00%
	Entertainment & Recreation	25	16	0	0	9,028,000	0	9,028,000	0	100.00%
6	Temporary Lodging	1	2	0	0	7,041,252	0	7,041,252	0	100.00%
Total retail		**230**	**76**	**14**	**0**	**22,993,870**	**46,950,993**	**69,944,863**	**0**	**100.00%**
Total entertainment		**189**	**110**	**8**	**3**	**122,409,806**	**451,621,698**	**572,625,387**	**1,406,117**	**99.76%**
Total Lodging		**54**	**54**	**1**	**0**	**24,424,406**	**6,840,590**	**31,264,996**	**0**	**100.00%**
Total EIA Scenario 2		473	240	23	3	169,828,082	505,413,281	673,835,246	1,406,117	99.79%

Model Areas	Occupancy Classes of interest	NN Protected	Exposed Sc4	Exit Sc4	Disruption With	Op Loss Without, $	Op Loss Exit, $	Prevented Loss (Without-With)	Op Loss With	Loss mitigation
	Retail Trade	21	5	3	2	1,391,090	41,247,032	42,484,233	153,889	99.64%
1	Entertainment & Recreation	14	6	1	0	5,729,271	34,061,342	39,790,613	0	100.00%
	Retail Trade	31	3	4	4	806,738	363,483,400	360,655,303	3,634,835	99.00%
	Entertainment & Recreation	34	11	3	1	7,195,653	147,902,103	153,618,736	1,479,020	99.05%
2	Temporary Lodging	7	0	0	0	0	0	0	0	-
	Retail Trade	76	23	11	4	5,688,273	462,844,417	468,105,755	426,935	99.91%
	Entertainment & Recreation	63	33	12	6	44,383,819	712,736,876	754,666,253	2,454,442	99.68%
3	Temporary Lodging	28	22	2	1	9,259,858	210,426,620	217,908,548	1,777,930	99.19%
	Retail Trade	7	1	3	0	130,184	14,823,141	14,953,325	0	100.00%
	Entertainment & Recreation	3	3	2	0	2,271,321	206,075,839	208,347,160	0	100.00%
4	Temporary Lodging	7	13	5	0	1,204,611	59,882,269	61,086,880	0	100.00%
	Retail Trade	66	10	15	0	2,592,107	253,742,966	256,335,073	0	100.00%
	Entertainment & Recreation	50	17	14	0	13,804,365	935,022,506	948,826,871	0	100.00%
5	Temporary Lodging	11	7	4	0	3,012,899	127,110,416	130,123,315	0	100.00%
	Retail Trade	29	8	4	0	1,025,070	36,375,513	37,400,583	0	100.00%
	Entertainment & Recreation	25	9	7	0	4,981,135	404,686,546	409,667,681	0	100.00%
6	Temporary Lodging	1	2	0	0	7,041,252	0	7,041,252	0	100.00%
Total retail		**230**	**50**	**40**	**10**	**11,633,462**	**1,172,516,469**	**1,179,934,272**	**4,215,659**	**99.64%**
Total entertainment		**189**	**79**	**39**	**7**	**78,365,564**	**2,440,485,212**	**2,514,917,314**	**3,933,462**	**99.84%**
Total Lodging		**54**	**44**	**11**	**1**	**20,518,620**	**397,419,305**	**416,159,995**	**1,777,930**	**99.57%**
Total EIA Scenario 4		**473**	**173**	**90**	**18**	**110,517,646**	**4,010,420,986**	**4,111,011,581**	**9,927,051**	**99.76%**

Tables 21-23. Economic benefits and residual losses for planning scenarios for economic subcategories. Short-term scenarios (top), long-term RCP`s 4.5 (middle) and 8.5 (bottom)

Appendix 05.

Charleston NbS performance with recreation multipliers

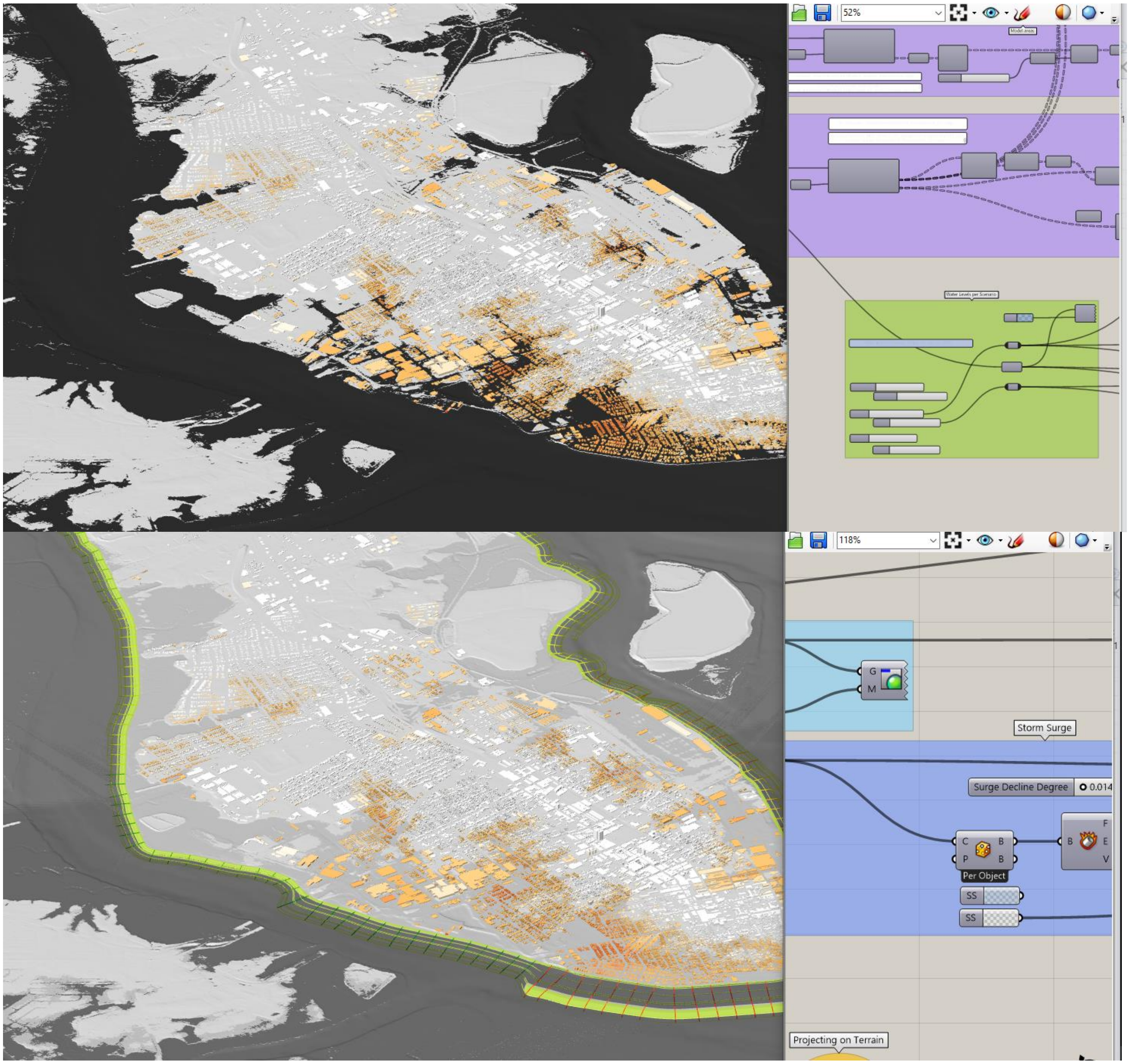
This module assumes that greener and more walkable public spaces attract recreation, tourism, and other resilient human activities. The City of Charleston hosted 6.9 million visitors in 2018 according to Convention and Visitors Bureau (Munday, 2018), making up the ratio of tourists to residents approximately 47:1 (The Office of Tourism Analysis, 2017). A rapid growth in tourism of 63.51% over the last decades caused the efforts of more effective management, such as “Charleston Charter for Sustainable Tourism”, special Overlay Districts and other measures for enhancing resilience (Tourism Mgmt Plan, 2015 update, p. 9, 2015; Dolan, 2018). Nevertheless, the visitors flow is essential for the economy, and its patters multiply the potential visitors spending in historically and recreationally attractive areas. Based on the National Parks, National Register of Historic places, and commercial services data, the last module assessed the potential growth of the attractiveness across the model areas. The results are shown in the Figures 24-26.

Model Areas	NbS	Occupancy Classes of interest	Protected, Nn Sc 1,3	Exposure, Nn Sc 1,3	Disruption With NbS, Nn Sc 1,3	Disruption Prevented, Nn, Sc 1,3	Disruption Prevented, %
1 - NOMO	Dikes/ Levees/ Oyster	Retail Trade	27	2	0	2	100.00%
		Entertainment & Recreation	21	0	0	0	-
2 - Port	Living bulkheads with ripraps	Retail Trade	38	0	0	0	-
		Entertainment & Recreation	47	1	0	1	100.00%
		Temporary Lodging	7	0	0	0	-
3 - East Bay	Dikes/ Levees/ Oyster	Retail Trade	106	4	0	4	-
		Entertainment & Recreation	102	6	0	6	100.00%
		Temporary Lodging	51	1	0	1	100.00%
4 - Battery	Barrier Island	Retail Trade	9	2	0	2	100.00%
		Entertainment & Recreation	6	2	0	2	100.00%
		Temporary Lodging	22	3	0	3	100.00%
5 - Marina	Wetlands restoration	Retail Trade	83	8	0	8	100.00%
		Entertainment & Recreation	72	9	0	9	100.00%
		Temporary Lodging	20	2	0	2	100.00%
6 - Waggener Terrace	Horizontal levee	Retail Trade	39	2	0	2	100.00%
		Entertainment & Recreation	37	4	0	4	100.00%
		Temporary Lodging	3	0	0	0	-
Total retail			302	18	**0**	**18**	**100.00%**
Total entertainment			285	22	**0**	**22**	**100.00%**
Total Lodging			103	6	**0**	**6**	**100.00%**
Total EIA Scenario 2			690	46	0	46	100.00%

Model Areas	NbS	Occupancy Classes of interest	Protected, Nn Sc 2	Exposure, Nn Sc 2	Exit, Nn Sc 2	Disruption With NbS, Nn Sc 2	Disruption Prevented, Nn, Sc 2	Disruption Prevented, %
1 - NOMO	Dikes/ Levees/ Oyster	Retail Trade	21	1	7	0	8	100.00%
		Entertainment & Recreation	14	7	0	0	7	100.00%
2 - Port	Living bulkheads with ripraps	Retail Trade	31	7	0	0	7	100.00%
		Entertainment & Recreation	34	14	0	1	13	92.86%
		Temporary Lodging	7	0	0	0	0	-
3 - East Bay	Dikes/ Levees/ Oyster	Retail Trade	76	33	1	0	34	100.00%
		Entertainment & Recreation	63	43	2	2	43	95.56%
		Temporary Lodging	28	24	0	0	24	100.00%
4 - Battery	Barrier Island	Retail Trade	7	2	2	0	4	100.00%
		Entertainment & Recreation	3	3	2	0	5	100.00%
		Temporary Lodging	7	18	0	0	18	100.00%
5 - Marina	Wetlands restoration	Retail Trade	66	23	2	0	25	100.00%
		Entertainment & Recreation	50	27	4	0	31	100.00%
		Temporary Lodging	11	10	1	0	11	100.00%
6 - Waggener Terrace	Horizontal levee	Retail Trade	29	10	2	0	12	100.00%
		Entertainment & Recreation	25	16	0	0	16	100.00%
		Temporary Lodging	1	2	0	0	2	100.00%
Total retail			230	76	14	**0**	**90**	**100.00%**
Total entertainment			189	110	8	**3**	**115**	**97.46%**
Total Lodging			54	54	1	**0**	**55**	**100.00%**
Total EIA Scenario 2			473	240	23	3	260	98.86%

Model Areas	NbS	Occupancy Classes of interest	Protected, Nn Sc 4	Exposure, Nn Sc 4	Exit, Nn Sc 4	Disruption With NbS, Nn Sc 4	Disruption Prevented, Nn, Sc 4	Disruption Prevented, %
1 - NOMO	Dikes/ Levees/ Oyster	Retail Trade	21	5	3	2	6	75.00%
		Entertainment & Recreation	14	6	1	0	7	100.00%
2 - Port	Living bulkheads with ripraps	Retail Trade	31	3	4	4	3	42.86%
		Entertainment & Recreation	34	11	3	1	13	92.86%
		Temporary Lodging	7	0	0	0	0	-
3 - East Bay	Dikes/ Levees/ Oyster	Retail Trade	76	23	11	4	30	88.24%
		Entertainment & Recreation	63	33	12	6	39	86.67%
		Temporary Lodging	28	22	2	1	23	95.83%
4 - Battery	Barrier Island	Retail Trade	7	1	3	0	4	100.00%
		Entertainment & Recreation	3	3	2	0	5	100.00%
		Temporary Lodging	7	13	5	0	18	100.00%
5 - Marina	Wetlands restoration	Retail Trade	66	10	15	0	25	100.00%
		Entertainment & Recreation	50	17	14	0	31	100.00%
		Temporary Lodging	11	7	4	0	11	100.00%
6 - Waggener Terrace	Horizontal levee	Retail Trade	29	8	4	0	12	100.00%
		Entertainment & Recreation	25	9	7	0	16	100.00%
		Temporary Lodging	1	2	0	0	2	100.00%
Total retail			230	50	40	**10**	**80**	**88.89%**
Total entertainment			189	79	39	**7**	**111**	**94.07%**
Total Lodging			54	44	11	**1**	**54**	**98.18%**
Total EIA Scenario 2			473	173	90	18	245	93.16%

Figures 24-26. Adaptation capacity of the NbS across Model areas and planning scenarios.



Figures 27-28. Exposure to flood risks under scenario 2 - algorithm and the outputs. "Without the project" (top), and "with the project" (bottom).

SOURCES

● Aerts, J.C.J.H., Barnard, P.L., Botzen, W., Grifman, P., Hart, J.F., De Moel, H., Mann, A.N., de Ruig, L.T., Sadrpour, N., 2018a. Pathways to resilience: adapting to sea level rise in Los Angeles. Ann. N. Y. Acad. Sci. 1427, 1–90. https://doi.org/10.1111/nyas.13917.

● Carl C. Anderson, Fabrice G. Renaud, Stuart Hanscomb, Alejandro Gonzalez-Ollauri, Green, hybrid, or grey disaster risk reduction measures: What shapes public preferences for nature-based solutions?, Journal of Environmental Management, Volume 310, 2022, 114727, ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2022.114727.

https://www.sciencedirect.com/science/article/pii/S0301479722003000

● Arkema, K.K., Guannel, G., Verutes, G., Wood, S. a., Guerry, A., Ruckelshaus, M., Kareiva, P., Lacayo, M., Silver, J.M., 2013. Coastal habitats shield people and property from sea-level rise and storms. Nat. Clim. Change 3, 1e6."

● Baig, S. P., Rizvi, A., Josella, M., Palanca-Tan, R. 2016. Cost and Benefits of Ecosystem Based Adaptation: The Case of the Philippines. Gland, Switzerland: IUCN. viii + 32pp.

● Edward B. Barbier,Sally D. Hacker,Chris Kennedy,Evamaria W. Koch,Adrian C. Stier,Brian R. Silliman. 2011. The value of estuarine and coastal ecosystem services https://doi.org/10.1890/10-1510.1

● Balachandran, Balakrishnan, Robert B. Olshansky, and Laurie A. Johnson. (2021). Planning for Disaster-Induced Relocation of Communities. Journal of the American Planning Association. Doi: 10.1080/01944363.2021.1978855.

● Barbier, E.B., Georgiou, I.Y., Enchelmeyer, B., Reed, D.J., 2013. The value of wetlands in protecting southeast Louisiana from hurricane storm surges. PLoS ONE 8.

- Edward B. Barbier,Sally D. Hacker,Chris Kennedy,Evamaria W. Koch,Adrian C. Stier,Brian R. Silliman. 2011. The value of estuarine and coastal ecosystem services. https://doi.org/10.1890/10-1510.1Citations: 2,779
- Basker, Emek, and Javier Miranda. 2014. "Taken by Storm: Business Financing, Survival, and Contagion in the Aftermath of Hurricane Katrina." University of Missouri Working Paper 1406.
- Bernstein Asaf, Matthew T. Gustafson, and Ryan Lewis. (2019). Disaster on the horizon: The price effect of sea level rise. Journal of Financial Economics, 134, 25 – 272.
- Berke, P. R., & Campanella, T. J. (2006). Planning for Postdisaster Resiliency. The Annals of the American Academy of Political and Social Science, 604, 192–207. http://www.jstor.org/stable/25097788
- Berke, P., J. Cooper, M. Aminto, S. Grabich, and J. Horney. 2014. "Adaptive planning for disaster recovery and resiliency: An evaluation of 87 local recovery plans in eight states." J. Am. Plann. Assoc. 80 (4): 310–323. https://doi.org/10.1080/01944363.2014.976585.
- Berke P, Newman G, Lee J, Combs T, Kolosna C, & Salvesen D (2015). Evaluation of Networks of Plans and Vulnerability to Hazards and Climate Change: A Resilience Scorecard. Journal of the American Planning Association, 81(4), 287–302
- Berke, P., & Godschalk, D. 2009. Searching for the good plan: A meta-analysis of plan quality studies. Journal of Planning Literature, 23(3), 227–240. doi:10.1177/0885412208327014 Godschalk, D. (2003). Urban hazard mitigation: Creating resilient cities. Natural Hazards Review, 4(3), 136–143. doi:10.1061/(ASCE)1527-6988(2003)4:3(136)

● Marcia Berman, Harry Berquist, Julie Herman, Karinna Nunez, 2007.Last update: 02 August 2016. THE STABILITY OF LIVING SHORELINES - AN EVALUATION Virginia Institute of Marine Science

● K. Van der Biest, L. De Nocker, S. Provoost, A. Boerema, J. Staes, P. Meire, 2017, Dune dynamics safeguard ecosystem services, Ocean & Coastal Management, Volume 149, Pages 148-158, ISSN 0964-5691, https://doi.org/10.1016/j.ocecoaman.2017.10.005. https://www.sciencedirect.com/science/article/pii/S096456911730131X

● Biohabitats, inc., One Architecture & Urbanism, 2020. Imagine The Wall. https://static1.squarespace.com/static/5eda715165bf83268529a936/t/61e6d80ad83e09266c5f1bf7/1642518560151/Imagine+the+Wall_reVision+Spreads+200922.pdf

● Boeing, G. (2019). "Nature-Based Solutions for Coastal Erosion and Flooding." Coastal Management, 47(3), 171-178. doi:10.1080/08920753.2019.1576709

● Bresch, D. N., Franke, J., Frank, C., & Huggel, C. (2018). CLIMADA v1. 4.0: A user-friendly, probabilistic tool for assessing the impacts of climate change on socio-economic assets. Geoscientific Model Development, 11(2), 865-880.

● Bridges, T.S., M. Bennion, M. Brown, L. Firth, M. Hooper, D. Moore, D. Scavia, A. Souza, T. Whigham, and E. Wolanski. (2021). NNBF International Guidelines on Natural and Nature-Based Features for Flood Risk Management. NNBF Working Group, USA.

● Brody, Samuel, et al. (2021). Chapter 1: “A Comprehensive Framework for Coastal Flood-Risk Reduction: Charting a Course Toward Resiliency.” in A Blueprint for Coastal Adaptation. Eds. C. Kousky, B. Fleming, and A.M. Berger. Washington, D.C.: Island Press. Pages 2 – 28.

● Katharine Burgess, Dr Elizabeth Rapoport, 2019, Climate Risk and Real Estate Investment Decision-Making, ULI , Heitman

● IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001.

● K. F. Cann, D. Rh. Thomas, R. L. Salmon, A. P. Wyn-Jones And D. Kay, 2013. Systematic Review: Extreme water-related weather events and waterborne disease. Epidemiology and Infection , APRIL 2013, Vol. 141, No. 4. https://www.jstor.org/stable/23360748

● CCRIF 2010 Caribbean Catastrophe Risk Insurance Facility. Enhancing the Climate Risk and Adaptation Fact Base for the Caribbean

● Chamberlain, C. (2020). Charleston flood study envisions walls to block surging seas, but not everyone is sold.

● Charleston Resilience Network. (2018). "CRN Response to USACE Peninsula Study." Retrieved from https://drive.google.com/file/d/1HjSdPY6JWUsPF1fQ2zif4gsO4oJgckf6/view

● Charleston City Paper. (2020). Critics say US Army Corps Charleston flood study misses mark on equity, climate change. https://www.charlestoncitypaper.com/story/critics-say-us-army-corps-charleston-flood-study-misses-mark-on-equity-climate-change

● Charleston City Plan, 2021. https://www.charlestoncityplan.com/

● Charleston Area Convention and Visitors Bureau. (n.d.). Reasons to Visit. https://www.charlestoncvb.com/plan-your-trip/reasons-to-visit/

● Charleston Metro Chamber of Commerce. (2021). Economic Impact of Tourism in Charleston Metro Region. https://www.charlestonchamber.org/wp-content/uploads/2021/07/2021-Economic-Impact-of-Tourism-in-Charleston-Metro-Region.pdf

● Charleston Area Convention and Visitors Bureau. (2021). Visitor Profile Study. https://www.charlestoncvb.com/wp-content/uploads/2021/03/2021-Charleston-Visitor-Profile-Study.pdf

● Chausson, A, Turner, B, Seddon, D, et al. Mapping the effectiveness of Nature-based Solutions for climate change adaptation. Glob Change Biol. 2020; 26: 6134– 6155. https://doi.org/10.1111/gcb.15310

● Chausson, A, Turner, B, Seddon, D, et al. Mapping the effectiveness of Nature-based Solutions for climate change adaptation. Glob Change Biol. 2020; 26: 6134– 6155. https://doi.org/10.1111/gcb.15310

● Chen Wen L., Muller Peter, Grabowski Robert C., Dodd Nicholas. 2022. Green Nourishment: An Innovative Nature-Based Solution for Coastal Erosion. Frontiers in Marine Science. VOLUME 8. https://www.frontiersin.org/articles/10.3389/fmars.2021.814589. 10.3389/fmars.2021.814589

● Chinowsky, P., Price, J. & Neumann, J. Assessment of climate change adaptation costs for the U.S. road network. Glob. Environ. Change 23, 764–773 (2013).

● City Of Charleston Civic Design Center, 2021. Charleston Peninsula 3x3x3. Civic design opportunities.

● Clark, P., Shakun, J., Marcott, S. et al. Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. Nature Clim Change 6, 360–369 (2016). https://doi.org/10.1038/nclimate2923

● Climate Central. (n.d.). Sea level rise and coastal flooding impacts. Retrieved April 19, 2023, from https://www.climatecentral.org/research/sealevelrise

● Coastal Conservation League, Sherwood Associates. 2021. Beyond The Wall. An Exploration Of Alternative Strategies To The Corps Seawall Proposal For Charleston, South Carolina. https://www.coastalconservationleague.org/projects/charleston-peninsula-coastal-flood-risk-management-study-by-the-us-army-corps-of-engineers/
https://storymaps.arcgis.com/stories/b931809990d347ab83ab990bd7592ea9

● Cohen-Shacham, Emmanuelle, Gretchen Walters, Christine Janzen and Stewart Maginnis, eds. (2016). Nature-based Solutions to address global societal challenges. Gland, Switzerland: IUCN. xiii + 97pp. https://www.iucn.org/sites/dev/files/content/documents/nature-based_solutions_to_address_global_societal_challenges.pdf.

● DeConto, R., Pollard, D. Contribution of Antarctica to past and future sea-level rise. Nature 531, 591–597 (2016). https://doi.org/10.1038/nature17145

● Costanza, R., Perez-Maqueo, O., Luisa Martinez, M., Sutton, P., Anderson, S.J., Mulder, K., 2008. The value of coastal wetlands for hurricane protection. AMBIO 37, 241–248.

● N. Edward Coulson, Shawn J. McCoy, Ian K. McDonough, Economic diversification and the resiliency hypothesis: Evidence from the impact of natural disasters on regional housing values, Regional Science and Urban Economics, Volume 85, 2020, 103581, ISSN 0166-0462, https://doi.org/10.1016/j.regsciurbeco.2020.103581.
(https://www.sciencedirect.com/science/article/pii/S0166046220302660)

● Credit Suisse, IUCN, Gordon and Betty Moore Foundation, The Rockefeller Foundation and Mckinsey Center for Business and Environment (2016). Conservation Finance from Niche to Mainstream: The Building of an Institutional Asset Class. https://www.credit-suisse.com/media/assets/corporate/docs/about-us/responsibility/banking/conservation-finance-en.pdf

- Davlasheridze, Meri, et al. "Economic Impacts of Storm Surge and the Cost-Benefit Analysis of a Coastal Spine as the Surge Mitigation Strategy in Houston-Galveston Area in the USA." Mitigation and Adaptation Strategies for Global Change, vol. 24, no. 3, 2019, pp. 329–54, https://doi.org/10.1007/s11027-018-9814-z
- Joseph DeAngelis, June 2018. Zoning for Coastal Flood Resilience. Zoning Practice
- Dyckman, Caitlin, Courtney St. John and James London. (2014). Realizing Managed Retreat and Innovation in State-Level Coastal Management Planning. Ocean & Coastal Management 102, 212 – 223.
- Dyckman, C. S., St. John, C., & London, J. B. (2014). Realizing managed retreat and innovation in state-level coastal management planning. Ocean and Coastal Management, 102, 212–223.
- ECA 2009 Economics of Climate Adaptation. A report of the economics of climate adaptation working group. A framework for decision-making.
- Emerton, Lucy, 2014. Valuing the Benefits, Costs and Impacts of Ecosystem-based Adaptation Measures. A sourcebook of methods for decision-making. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Bonn and Eschborn, Germany
- European Environmental Agency, 2021. Global and European sea level rise. https://www.eea.europa.eu/ims/global-and-european-sea-level-rise
- European Parliament (2017). Nature-Based Solutions: Concept, Opportunities, and Challenges.

https://www.europarl.europa.eu/RegData/etudes/BRIE/2017/608796/EPRS_BRI(2017)608796_EN.pdf

- FEMA, 2009. Benefit-Cost Analysis Reference Guide. Federal Emergency Management Agency. Department of Homeland Security
- Federal Emergency Management Agency. (2017). Hazus-MH MR4 Technical Manual.
- Gardner, T. W. (2018). In the Wake of the Storm: A Comparative Analysis of Disaster Response and Recovery Strategies in Charleston, South Carolina. Journal of Planning Education and Research, 38(2), 142-156.
- Gedan KB, Kirwan MJ, Wolanski E, Barbier EB, Silliman BR (2011) The present and future role of coastal vegetation in protecting shorelines: answering recent challenges to the paradigm. Climatic Change 106: 7–29.
- Godschalk, David R., Timothy Beatley, Philip Berke, David J. Brower, and Edward J. Kaiser. (1999). Natural Hazard Mitigation: Recasting Disaster Policy and Planning.
- Godschalk, D.R., Rose, A., Mittler, E., Porter, K., West, C.T., 2009. Estimating the value of foresight: aggregate analysis of natural hazard mitigation benefits and costs. J. Environ. Plann. Manage. 52 (6), 739–756. https://doi.org/10.1080/09640560903083715.
- Nina Graveline, Marine Grémont, Measuring and understanding the microeconomic resilience of businesses to lifeline service interruptions due to natural disasters, International Journal of Disaster Risk Reduction, Volume 24, 2017, Pages 526-538, ISSN 2212-4209, https://doi.org/10.1016/j.ijdrr.2017.05.012.
(https://www.sciencedirect.com/science/article/pii/S2212420916305295)

- Guerry, A.D., Silver, J., Beagle, J. et al. Protection and restoration of coastal habitats yield multiple benefits for urban residents as sea levels rise. npj Urban Sustain 2, 13 (2022). https://doi.org/10.1038/s42949-022-00056-y
- Hallegatte, S., Green, C., Nicholls, R.J., Corfee-Morlot, J., 2013. Future flood losses in major coastal cities. Nature Clim. Change 3 (9), 802–806.
- Liselotte C. Hagedoorn*, 2021. "Estimating Benefits of Nature-based Solutions: Diverging Values From Choice Experiments With Time or Money Payments. www.frontiersin.org Mark J. Koetse and www.frontiersin.orgPieter J. H. van Beukering Institute for Environmental Studies (IVM), Vrije Universiteit, Amsterdam, Netherlands"
- https://doi.org/10. 1038/nclimate1979.
- Hadideh, S., 2019. "Opportunities and Challenges of Public Participation in Post-Disaster Recovery Planning: Lessons from Galveston, TX". Natural Hazards Review, vol 21, Iss 4, American Society of Civil Engineers, https://doi.org/10.1061/(ASCE)NH.1527-6996.0000399
- Haley, L. (2019). Living Breakwaters: How Innovative Design Could Help Save Charleston's Coastline. Charleston City Paper. Retrieved from https://www.charlestoncitypaper.com/charleston/living-breakwaters-how-innovative-design-could-help-save-charlestons-coastline/Content?oid=28526197
- Holland, E., & Burnette, C. (2018). "The Future of Floodplain Management in Charleston, SC." The Palmetto Engineer, 26(1), 10-14.
- Hsiang, Solomon M. and Daiju Narita. 2012. “Adaptation to Cyclone Risk: Evidence from the Global Cross-Section.” Climate Change Economics 3 (2)

● Robert Jeffers and Bill Rhodes. July 06 2016. Development of an Urban Resilience Analysis Framework. Application to Norfolk, VA and New Oreans, LA. Presentation to 100 Resilient Cities.

● Johnson, L. A. 2014b. "Long-term recovery planning: The process of planning." In Planning for post-disaster recovery: Next generation, edited by J. C. Schwab. Chicago: American Planning Association. https://www.fema.gov/sites/default/files/2020-06/apa_planning-for-post-disaster-recovery-next-generation_03-04-2015.pdf

● Kazmierczak, A., Carter, J., 2010. Adaptation to Climate Change Using Green and Blue Infrastructure. A Database of Case Studies. University of Manchester, School of Environment, Education, and Development, Manchester, England.

● Jesse M. Keenan and Claire Weisz. Blue Dunes. Climate Change by Design. Columbia Books on Architecture and the City

● Kirezci, E., Young, I.R., Ranasinghe, R. et al. Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. Sci Rep 10, 11629 (2020). https://doi.org/10.1038/s41598-020-67736-6

● Koch EW, Barbier EB, Silliman BR, Reed DJ, Perillo GME, et al. (2009) Nonlinearity in ecosystem services: temporal and spatial variability in coastal protection. Frontiers in Ecology & the Environment 7: 29–37.

● Kocornik-Mina A, McDermott T K, Michaels G and Rauch F, 2020. "Flooded cities" Am. Econ. J.: Appl. Econ. 12 35–66. https://www.aeaweb.org/articles?id=10.1257/app.20170066

● Kopp, R. E., DeConto, R. M., Bader, D. A., Hay, C. C., Horton, R. M., Kulp, S., Oppenheimer, M., Pollard, D., & Strauss, B. H. (2017). Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections. Earth's Future, 5(12), 1217-1233. doi: 10.1002/2017EF000663

● Kopp R, Gilmore E, Little C, Lorenzo-Trueba J, Ramenzoni V and Sweet W, 2019. Usable science for managing the risks of sea-level rise Earth’s Future 7 1235–69. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2018EF001145

● Kousky, Carolyn. (2021). Chapter 12 "Coastal Urbanism: Designing the Future Waterfront” Rafi Segal and Susannah Drake In A Blueprint for Coastal Adaptation. Eds. C. Kousky, B. Fleming, and A.M. Berger. Washington, D.C.: Island Press.

● Kousky, C., Shabman, L., 2017. Federal funding for flood risk reduction in the US: Pre-or post-disaster? Water Econ. Policy 3(01). Available doi: 10.1142/S2382624X17710011.

● Prashant Kumar, Sisay E. Debele, Jeetendra Sahani, Nidhi Rawat, Belen Marti-Cardona, Silvia Maria Alfieri, Bidroha Basu, Arunima Sarkar Basu, Paul Bowyer, Nikos Charizopoulos, Glauco Gallotti, Juvonen Jaakko, Laura S. Leo, Michael Loupis, Massimo Menenti, Slobodan B. Mickovski, Seung-Jae Mun, Alejandro Gonzalez-Ollauri, Jan Pfeiffer, Francesco Pilla, Julius Pröll, Martin Rutzinger, Marco Antonio Santo, Srikanta Sannigrahi, Christos Spyrou, Heikki Tuomenvirta, Thomas Zieher. 2021. Nature-based solutions efficiency evaluation against natural hazards: Modelling methods, advantages and limitations, Science of The Total Environment, Volume 784, 147058, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2021.147058. (https://www.sciencedirect.com/science/article/pii/S0048969721021288)

● Suzanne M. Langridge, Eric H. Hartge, Ross Clark, Katie Arkema, Gregory M. Verutes, Erin E. Prahler, Sarah Stoner-Duncan, David L. Revell, Margaret R. Caldwell, Anne D. Guerry, Mary Ruckelshaus, Adina Abeles, Chris Coburn, Kevin O'Connor, Key lessons for incorporating natural infrastructure into regional climate adaptation planning, Ocean & Coastal Management, Volume 95, 2014, Pages 189-197, ISSN 0964-5691,

https://doi.org/10.1016/j.ocecoaman.2014.03.019.

- Leiter, A.M., Oberhofer, H., Raschky, P.A., 2009. Creative Disasters? Flooding effects on capital, labour and productivity within European firms. Environ. Res. Econ. 43, 333–350.
- Leuven, J.R.F.W., Pierik, H.J., Vegt, M.v.d. et al. Sea-level-rise-induced threats depend on the size of tide-influenced estuaries worldwide. Nat. Clim. Chang. 9, 986–992 (2019). https://doi.org/10.1038/s41558-019-0608-4
- Bongarts Lebbe, T., Beguin Billecocq, I., Vegh, T., & Sarkozy-Banoczy, S. (2022) Investment Protocol: Unlocking Financial Flows for Coastal Cities Adaptation to Climate Change and Resilience Building. Blue-tinted white paper. Race to Resilience, High-Level Climate Champions.
- Lopez, J.A. 2009 The multiple lines of defense strategy to sustain coastal Louisiana. Journal of Coastal Research SI (54): 186–197.
- Lin, N., Emanuel, K., Oppenheimer, M., Vanmarcke, E., 2012. Physically based assessment of hurricane surge threat under climate change. Nature Clim. Change 2 (6), 462. https://doi.org/10.1038/nclimate1389.
- Loayza, Norman, Olaberría, Eduardo, Rigolini, Jamele, Christiansen, Luc, 2012. Natural disasters and growth-going beyond the averages. World Dev. 40 (7), 1317–1336.
- Maes, Joaquin, and Sander Jacobs (2015). Nature-Based Solutions for Europe’s Sustainable Development. Conservation Letters 10(1): 121-124. https://conbio.onlinelibrary.wiley.com/doi/pdf/10.1111/conl.12216.

- Maler, K., Li, C. Z., and Destouni, G. 2007. Pricing resilience in a dynamic economy-environment system: A capital-theoretical approach. Beijer Discussion Papers 208, Royal Swedish Academy of Sciences, Stockholm.
- Martinich J, Crimmins A (2019) Climate damages and adaptation potential across diverse sectors of the United States. Nat. Clim. Change 9:397–404
- Masselink, G., & Lazarus, E. D. (2019). Defining coastal resilience. Water, 11(12), 2587. doi:https://doi-org.libproxy.clemson.edu/10.3390/w11122587
- Sadie McEvoy, Marjolijn Haasnoot, Robbert Biesbroek, 2021. "How are European countries planning for sea level rise?" Ocean & Coastal Management, Volume 203, 105512, ISSN 0964-5691, https://doi.org/10.1016/j.ocecoaman.2020.105512. https://www.sciencedirect.com/science/article/pii/S0964569120304191
- (https://www.sciencedirect.com/science/article/pii/S0169204622000238)
- Moraes Roberta P. L., Reguero Borja G., Mazarrasa Inés, Ricker Max, Juanes José A. 2022. Nature-Based Solutions in Coastal and Estuarine Areas of Europe. Frontiers in Environmental Science, VOLUME=10 https://www.frontiersin.org/articles/10.3389/fenvs.2022.829526. DOI=10.3389/fenvs.2022.829526
- Narayan, S., Beck, M.W., Wilson, P. et al. The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA. Sci Rep 7, 9463 (2017). https://doi.org/10.1038/s41598-017-09269-z
- Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2011). Soil and Water Assessment Tool Theoretical Documentation: Version 2009. Texas Water Resources Institute.
- Edward Ng and Chao Ren, The Urban Climatic Map for Sustainable Urban Planning, published 2015 by Routledge, ch 27, 29

- Nhung T.H. Nguyen, Daniel A. Friess, Peter A. Todd, Tessa Mazor, Catherine E. Lovelock, Ryan Lowe, James Gilmour, Loke Ming Chou, Natasha Bhatia, Zeehan Jaafar, Karenne Tun, Siti Maryam Yaakub, Danwei Huang, Maximising resilience to sea-level rise in urban coastal ecosystems through systematic conservation planning, Landscape and Urban Planning, Volume 221, 2022, 104374, ISSN 0169-2046, https://doi.org/10.1016/j.landurbplan.2022.104374.
- Noble, I.R., Huq, S., Anokhin, Y.A., Carmin, J., Goudou, D., Lansigan, F.P., Osman-Elasha, B., Villamizar, A., 2014. Adaptation needs and options. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, pp. 833–868.
- OECD (2019), "Emerging approaches to coastal adaptation", in Responding to Rising Seas: OECD Country Approaches to Tackling Coastal Risks, OECD Publishing, Paris, https://doi.org/10.1787/b01ad17a-en.
- OECD, 2019, Responding to Rising Seas: OECD Country Approaches to Tackling Coastal Risks, OECD Publishing, Paris, https://doi. org/10.1787/9789264312487-en.
- Pasquali, D., & Marucci, A. (2021). The effects of urban and economic development on coastal zone management. Sustainability, 13(11), 6071. doi:https://doi-org.libproxy.clemson.edu/10.3390/su13116071
- Peiwen Lu, Dominic Stead, 2013. "Understanding the notion of resilience in spatial planning: A case study of Rotterdam, The Netherlands". Cities, Volume 35, Pages 200-212,

ISSN 0264-2751, https://doi.org/10.1016/j.cities.2013.06.001. https://www.sciencedirect.com/science/article/pii/S0264275113000851

- Peterson, Jeffrey. (2019). A New Coast: Strategies for Responding to Devastating Storms and Rising Seas. Washington, D.C.: Island Press
- Post and Courier. (2020). Charleston flood study meets pushback from community advocates. The Post and Courier. https://www.postandcourier.com/news/charleston-flood-study-meets-pushback-from-community-advocates/article_b2c0d162-0a04-11eb-8aae-1f69dd5ba834.html
- Powell, E.J., Tyrrell, M.C., Milliken, A. et al. A review of coastal management approaches to support the integration of ecological and human community planning for climate change. J Coast Conserv 23, 1–18 (2019). https://doi.org/10.1007/s11852-018-0632-y
- Quinn, C. E., Cooper, J. A., & Mendelssohn, I. A. (2019). Assessing the economic viability of nature-based solutions for coastal hazards mitigation: a cost–benefit analysis in the Gulf of Mexico. Environmental Science & Technology, 53(12), 6949-6960. doi: 10.1021/acs.est.8b06651
- Leander Raes, Damien Mittempergher, Matías Piaggio and Juha Siikamäki. 2021. IUCN Economic Knowledge Unit, Nature-based Recovery can create jobs, deliver growth and provide value for nature, IUCN, Nature-based Recovery Initiative Technical Paper No. 3
- Raymond, C.M., Berry P., Breil M., Nita M. R., Kabisch N., de Bel M., Enzi V., Frantzeskaki N., Geneletti D., Cardinaletti M., Lovinger L., Basnou C., Monteiro A., Robrecht H., Sgrigna G., Munari L., Calfapietra C. (2017). An impact evaluation framework to support planning and evaluation of nature-based solutions projects. Report prepared by the EKLIPSE

Expert Working Group on Nature-based Solutions to Promote Climate Resilience in Urban Areas. Centre for Ecology & Hydrology, Wallingford, United Kingdom

● Borja G. Reguero, Michael W. Beck, David Schmid, Daniel Stadtmüller, Justus Raepple, Stefan Schüssele, Kerstin Pfliegner, Financing coastal resilience by combining nature-based risk reduction with insurance, Ecological Economics, Volume 169, 2020, 106487, ISSN 0921-8009, https://doi.org/10.1016/j.ecolecon.2019.106487.

● Lars T. de Ruig, Patrick L. Barnard, W.J. Wouter Botzen, Phyllis Grifman, Juliette Finzi Hart, Hans de Moel, Nick Sadrpour, Jeroen C.J.H. Aerts, An economic evaluation of adaptation pathways in coastal mega cities: An illustration for Los Angeles, Science of The Total Environment, Volume 678, 2019, Pages 647-659, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2019.04.308.

● Reguero, B.G. & Bresch, David & Beck, Michael & Calil, Juliano & Meliane, Imèn. (2014).Coastal risks, nature-based defenses and the economics of adaptation: an application in the gulf of Mexico, USA. Coastal Engineering Proceedings. 1. 10.9753/icce.v34.management.25.

● Reguero BG, Beck MW, Bresch DN, Calil J, Meliane I (2018) Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. PLOS ONE 13(4): e0192132. https://doi.org/10.1371/journal.pone.0192132

● Sallenger AH, Doran KS, Howd PA (2012) Hotspot of accelerated sea-level rise on the Atlantic coast of North America. Nat Clim Chang 2:884–888"

● Linda Shi, Andrew M. Varuzzo, Surging seas, rising fiscal stress: Exploring municipal fiscal vulnerability to climate change, Cities, Volume 100, 2020, 102658, ISSN 0264-2751, https://doi.org/10.1016/j.cities.2020.102658.
(https://www.sciencedirect.com/science/article/pii/S0264275118314100)"

● Schuster, E., Doerr, P., 2015. A guide for incorporating ecosystem service valuation into coastal restoration projects. The Nature Conservancy, New Jersey Chapter. Delmont, NJ.

● Seddon N, Chausson A,Berry P, Girardin CAJ, Smith A, Turner B. 2020Understanding the value and limits ofnature-based solutions to climate change andother global challenges.Phil. Trans. R. Soc. B375: 20190120.http://dx.doi.org/10.1098/rstb.2019.0120

● Sharp, R., Tallis, H.T., Ricketts, T., et al. (2016). InVEST User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy.

● Tien Shiao, Cora Kammeyer, Gregg Brill, Laura Feinstein, Michael Matosich, Kari Vigerstol and Carla Müller-Zantop (2020). Business Case for Nature-Based Solutions: Landscape Assessment. United Nations Global Compact CEO. Water Mandate and Pacific Institute. Oakland, California. www.ceowatermandate.org/nbs/landscape

● Erika Spanger-Siegfried, Kristina Dahl, Astrid Caldas, Shana Udvardy, Rachel Cleetus, Pamela Worth and Nicole Hernandez Hammer. (2017). When Rising Seas Hit Home: Hard Choices Ahead for Hundreds of U.S. Coastal Communities. Union of Concerned Scientists. Available from: https://www.ucsusa.org/resources/when-rising-seas-hit-home

● The State. (2020). New USACE report outlines proposals to protect Charleston from flooding. The State. https://www.thestate.com/news/local/article246882962.html

● Sandler and Schwab, Chapters 1 – 2, 10: "Hazards and Disasters, "Preparedness, Hazard Mitigation, and Climate Change" and "Risk Assessment: Identifying Hazards and Vulnerability.

● Yan Song, Chaosu Li, Robert Olshansky, Yang Zhang & Yu Xiao (2017): Arewe planning for sustainable disaster recovery? Evaluating recovery plans after the Wenchuanearthquake, Journal of Environmental Planning and Management http://dx.doi.org/10.1080/09640568.2017.1282346

- Kihwan Song, Yun-Eui Choi, Hyo-Joo Han, Jinhyung Chon, Adaptation and transformation planning for resilient social-ecological system in coastal wetland using spatial-temporal simulation, Science of The Total Environment, Volume 789, 2021, 148007, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2021.148007.
- Sundar, V., Sannasiraj, S. A., & Sukanya, R. B. (2022). Sustainable hard and soft measures for coastal protection – case studies along the indian coast. Marine Georesources and Geotechnology, 40(5), 600-615. doi:https://doi-org.libproxy.clemson.edu/10.1080/1064119X.2021.1920650
- Taylor, Judith, Norman S. Levine, Ernest Muhammad, Dwayne E. Porter, Annette M. Watson, and Paul A. Sandifer. 2022. "Participatory and Spatial Analyses of Environmental Justice Communities' Concerns about a Proposed Storm Surge and Flood Protection Seawall" International Journal of Environmental Research and Public Health 19, no. 18: 11192. https://doi.org/10.3390/ijerph191811192
- Alexandra Toimil, Pedro Díaz-Simal, Inigo J. Losada, Paula Camus, Estimating the risk of loss of beach recreation value under climate change, Tourism Management, Volume 68, 2018, Pages 387-400, ISSN 0261-5177, https://doi.org/10.1016/j.tourman.2018.03.024. (https://www.sciencedirect.com/science/article/pii/S0261517718300748)
- Richard S. J. Tol, Richard J. T. Klein, Robert J. Nicholls "Towards Successful Adaptation to Sea-Level Rise along Europe's Coasts," Journal of Coastal Research, 2008(242), 432-442, (1 March 2008)
- University of Oxford. (2019). Nature-Based Solutions Initiative. Oxford: University of Oxford Department of Zoology. https://www.naturebasedsolutionsinitiative.org/

● United States Army Corps of Engineers. (2015). Charleston peninsula study: Coastal storm risk management feasibility study. https://www.sac.usace.army.mil/Portals/43/docs/Civil%20Works/Charleston%20Peninsula%20Study/Charleston%20Peninsula%20Study%20Final%20Report%20with%20Appendices.pdf

● U.S. Army Corps of Engineers. (2016). HEC-RAS River Analysis System: Hydraulic Reference Manual. Davis, CA: Hydrologic Engineering Center.

● USACE, 2022. Charleston Peninsula Study. Coastal Storm Risk Management Study. Final Feasibility Report / Environmental Impact Statement.

● USACE, 2020. Charleston Peninsula Study. Economic Feasibility assessment https://www.sac.usace.army.mil/Portals/43/docs/civilworks/peninsulastudy/Draft%20IFR-EA/Draft%20Feasibility%20Report_EA.pdf

● USDA Natural Resources Conservation Service. (2011). WinTR-20: User's Manual.

● U.S. Geological Survey. (2011). Hydrologic Landscape Regions: A Framework for Managing Forested Landscapes for Water. USGS Circular 1368.

● Paul Voosen, 2022. “Global warming is speeding up ocean currents. Here’s why. Excess heat constricts water flow in shallow surface layers” Science. https://www.science.org/content/article/global-warming-speeding-ocean-currents-here-s-why

● de Vriend, Huib & van Koningsveld, Mark & Aarninkhof, Stefan. (2014). 'Building with nature': The new Dutch approach to coastal and river works. ICE Proceedings Civil Engineering. 167. 18-24. 10.1680/cien.13.00003.

● Wagonner and Ball, 2019. Dutch Dialogues Charleston. Historic Charleston Foundation, City of Charleston.

- Wedding LM, Reiter S, Moritsch M, Hartge E, Reiblich J, Gourlie D, Guerry A. Embedding the value of coastal ecosystem services into climate change adaptation planning. PeerJ. 2022 Aug 23;10:e13463. doi: 10.7717/peerj.13463. PMID: 36032941; PMCID: PMC9415443.
- Wiering, Marcus & Green, Colin & Rijswick, H.F.M.W. & Priest, Sally & Keessen, Andrea. (2015). The rationales of resilience in English and Dutch flood risk policies. Journal of Water and Climate Change. 6. 10.2166/wcc.2014.017.
- van Zelst, V.T.M., Dijkstra, J.T., van Wesenbeeck, B.K. et al. Cutting the costs of coastal protection by integrating vegetation in flood defences. Nat Commun 12, 6533 (2021). https://doi.org/10.1038/s41467-021-26887-4
- Ziyuan Luo, Jian Tian, Jian Zeng, Francesco Pilla, Resilient landscape pattern for reducing coastal flood susceptibility, Science of The Total Environment, Volume 856, Part 1, 2023, 159087, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2022.159087.