CLIMATE CHANGE ADAPTATION STRATEGIES FOR PROTECTED AREAS IN PUERTO RICO

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Climate Change Adaptation Strategies for Protected Areas in Puerto Rico

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Abstract

The goal of this project was to provide climate change adaptation strategies to supplement Para la Naturaleza’s existing management plans and protect ecosystems and infrastructure within the coastal areas of Las Cabezas de San Juan Nature Reserve and Área Natural Protegida Medio Mundo y Daguao. This was accomplished by assessing the two sites, prioritizing at-risk areas, and proposing adaptation strategies. We have proposed non-invasive adaptation strategies in two forms: general strategies to be broadly applied, as well as specific recommendations for areas within the two sites.

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Executive Summary

Climate change is a growing issue impacting natural and human systems around the world. Coastal regions are especially susceptible to the effects of climate change due to their proximity to the ocean, where many impacts manifest. Para la Naturaleza (PLN) is a private nonprofit organization that aims to monitor and protect various lands of high ecological value on the island of Puerto Rico (Para la Naturaleza, Who Are We?, n.d.). Unfortunately, PLN's existing management plans for protected areas do not address climate change, a problem affecting ecosystems and infrastructure within the areas. Other climate change management plans in use around the world are often vague and not comprehensive. Importantly, none of the management plans we examined focused on the challenges associated with implementing strategies in protected areas. The overall goal of our project was to provide recommendations for climate change adaptation strategies for Las Cabezas de San Juan Nature Reserve and Área Natural Protegida Medio Mundo y Daguao, which can be incorporated into future management plans for protected areas monitored by PLN. We aimed to create a standardized method for proposing adaptation strategies that can be extended to other regions. To accomplish this goal, we developed three main objectives:

1. **Assess the two sites selected by PLN to gauge the effects of climate change on existing infrastructure and natural systems**. This involved the analysis of existing management plans and the utilization of online software, such as the National Oceanic and Atmospheric Administration (NOAA) Sea Level Rise Viewer and the Interactive Map of Puerto Rico. In addition, we interviewed PLN employees and conducted site visits to better understand the condition of the reserves and the climate change impacts threatening each site.
2. **Prioritize the most critical areas, based on importance and vulnerability to climate change impacts**. The importance of each site within the reserve was determined based on cultural, ecological, tourism, and infrastructural factors. Vulnerability was assessed based on the site's susceptibility to sea level rise, coastal erosion, flooding, and extreme weather events.
3. **Identify potential adaptation strategies and perform a cost analysis**. We compiled strategies from existing management plans that could be applicable in the two protected areas. Any strategies that we proposed to PLN are as natural, subtle, and non-invasive as possible to maintain the natural appearance of these areas.

Results

Our assessment showed that both sites will be impacted by sea level rise (SLR) and will experience partial or complete inundation in important areas. At Las Cabezas de San Juan Nature Reserve, approximately 15% of land will be inundated after one foot of SLR, 30% after three feet of SLR, and 37% after six feet of SLR. At Área Natural Protegida Medio Mundo y Daguao, approximately 44% of land will be inundated after one foot of SLR, 55% after three feet of SLR, and 62% after six feet of SLR (The Government of Puerto Rico, 2015). These sites are also being threatened by other climate change impacts including coastal erosion, storm surges, increased precipitation, an increase in frequency and severity of natural disasters, ocean acidification, and flooding. Using the information from the assessment, we prioritized sites within each reserve based on their cultural, ecological, tourism, and infrastructural importance and vulnerability to climate change impacts. Within Las Cabezas de San Juan Nature Reserve, the sites are prioritized in the following order: access road, Playa Jayuya, Playa Canalejo, Laguna Grande, Seven Seas Beach, Playa Lirios, Visitor Center, El Faro, and the boardwalk. For Área Natural Protegida Medio Mundo y Daguao the sites were prioritized as follows: mangrove forest, Medio Mundo Beach, dirt road, visitor center, Langley Drive, bridge, and the boardwalk.

We gathered potential adaptation strategies from various sources to be proposed for the protected areas. Australia's CoastAdapt system, the San Juan Bay Estuary Climate Change Adaptation Plan, the Scottish Coastal Archeological and Problem of Erosion Trust (SCAPE) Model, and the Environmental Protection Agency's (EPA) *Synthesis of Adaptation Options for Coastal Areas* all contained useful adaptation strategies. (Australian Government Department of the Environment and Energy, 2019; Bauzá-Ortega, 2015; Dawson, 2013; U.S. EPA, 2009). We developed other strategies with help from PLN employees Santiago Oliver Báez, Pablo Ponce De León, and Antares Ramos Álvarez (Personal Communications, 2019). We compiled these strategies and then made recommendations for specific areas as applicable. We researched past uses of individual strategies and spoke with PLN employees to gather information on approximate costs of implementation. At a minimum, we were able to provide estimates of material costs. We also included costs for labor, transportation of materials, and monitoring when this information was available.

Conclusions

The protected areas we assessed will be, or are currently being impacted by, SLR, coastal erosion, storm surges, increased precipitation, an increase in frequency and severity of natural disasters, ocean acidification, and flooding. Critical areas in need of adaptation strategies within each site were identified as those that have the most relative value, are in the most danger from climate change impacts, or both. This reported that the access road and Playa Jayuya within Las Cabezas de San Juan and the coastal mangroves and dirt access road within Área Natural Protegida Medio Mundo y Daguao should be prioritized based on their importance and vulnerability.

Utilization of volunteers and implementation of a monitoring system are important to the success of the adaptation methods. Most, if not all, of the labor involved in implementing the adaptation strategies could be completed by volunteer groups under the supervision of knowledgeable experts. This would eliminate or reduce labor costs, leaving funds for other aspects. Once implemented, a method for monitoring is required for maintenance and determining the strategies' success (Fideicomiso de Conservación de Puerto Rico, 2010.a). This could consist of volunteers that collect data and observations at each of the sites, such as measuring and reporting rates of sea level rise or coastal erosion.

Most traditional strategies, particularly hard adaptation strategies, cannot be used in these protected areas. Because of high tourism rates and ecological vulnerability, it was necessary to consider alternative strategies, or combinations of several existing techniques to meet the needs of each area. It was essential to evaluate the aesthetic impacts of any strategies that are selected to preserve the natural appearance of these sites. An additional challenge is that some areas in the reserves are inaccessible making implementation more difficult.

It is difficult to define how quickly SLR is progressing and when impacts will begin. Organizations around the world have attempted to quantify SLR and make projections for the future. These projections typically come in the form of sea level increase from current levels to those expected in the year 2100. The high end of these projections predict a 5.9 foot SLR by the year 2100 (Ezcurra & Rivera, 2018). Low ends of similar projections indicate increases in sea level of only 0.85 feet (IPCC, 2018). These discrepancies arise from unknown rates of future carbon dioxide emissions and glacial ice melt (NOAA Office for Coastal Management, n.d.). While there is no widespread agreement on the rate of SLR, most organizations agree on the fact that it is accelerating.

PLN recognizes the potential for partial or complete loss of their sites due to sea level rise and natural disasters, despite the efforts made. Elizabeth Padilla stated that within 100 years, they expect the reserve at Las Cabezas de San Juan to be a series of islands because of sea level rise (Personal Communication, 2019). In some cases, the best option may be to do nothing and focus efforts elsewhere, while allowing natural systems to adapt.

Recommendations for Ecosystems and Infrastructures

Roads

- Maintaining vegetation on the sides of roads can protect from erosion and inundation.
- Fortify edges of road through stone placement to reduce surface erosion.
- For a long-term solution, bridges with stable foundations could be built to raise the level of the road, accommodating rising water level.

Archaeological Sites

- Focusing excavation efforts on the regions most susceptible to climate change impacts will minimize the loss of archaeological artifacts.

Mangroves

- Dead mangroves should be removed in stages while planting in coastal areas that were damaged by hurricanes and storm surges.
- Begin planting new mangroves, using the remaining dead mangroves as protection. The belt of replanting can progressively be moved outward as time and resources are available.

Beaches

- Do not build hard structures (i.e. seawalls, jetties, etc.) because these structures will cause erosion or unintended effects at other locations.
- Replanting sea grasses or restoring and planting Staghorn and Elkhorn coral in coastal reefs to strengthen natural breakwater of the reefs.
- Dune development using sand fences or collecting and baling sargassum.

Built Infrastructure

- Consider GIS projections and build in areas which are less likely to be impacted by flooding and SLR.
- Adapt infrastructure by raising existing structures in at risk areas on stilts to protect from the effects of flood damage.
- Ensure existing structures are regularly inspected and maintained. Corrosion caused by changes in humidity can weaken structures and should be identified.
- Fortifying roofs to effectively drain water will reduce impacts of extreme weather events.

Authorship Page

Section	Primary Author(s)	Editors
Abstract	All	All
Executive Summary	All	All
1.0: Introduction	All	All
2.0: Background	All	All
2.1 Climate Change	Ari Athair	All
2.1.1 Impact of Climate Change on Ecosystems	Ari Athair	All
2.1.2: Impacts of Climate Change on Heritage Sites and Built Infrastructure	Dylan Parrow	All
2.2 Previous Research and Adaptation Strategies	Brooke DePascale	All
2.2.1 Approaches and Management Plans	Brooke DePascale	All
2.2.2 Types of Adaptation Strategies	Ari Athair	All
2.3: Major Stakeholders in Puerto Rico	Jacob Boles	All
2.4 Vulnerable Sites and Infrastructure in Puerto Rico	Dylan Parrow	All
3.0 Methodology	All	All
3.1 Assessment of Two Protected Areas	Brooke DePascale	All
3.1.1 Utilization of Online Software	Brooke DePascale	All
3.1.2 Evaluation of Existing Conditions	Brooke DePascale	All
3.2 Prioritization of Most Susceptible Areas	Dylan Parrow	All
3.3 Compilation of Potential Adaptation Strategies and Associated Costs	Ari Athair, Jacob Boles	All
4.0 Results and Analysis	All	All
4.1 Site Assessment of Protected Areas	Ari Athair, Jacob Boles, Brooke DePascale	All
4.2 Prioritization of Vulnerable Areas	Dylan Parrow	All
4.3 Potential Climate Change Adaptation Strategies	All	All
4.3.1 Application and Economic Analysis of Adaptation Strategies	All	All

5.0 Conclusions and Recommendations	All	All
5.1 Recommendations	All	All
5.1.1 General Strategies for Adaptation	All	All
5.1.2 Site Specific Recommendations	All	All
5.2 Future Work	Ari Athair	All

Table of Contents

List of Tables

List of Figures

List of Acronyms

C-CADS	Coastal Climate Adaptation Decision Support
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
MIPR	Interactive Map of Puerto Rico
NOAA	National Oceanic and Atmospheric Administration
PLN	Para la Naturaleza
PRCCC	Puerto Rican Climate Change Council
SAV	Submerged Aquatic Vegetation
SCAPE	Scottish Coastal Archeological and Problem of Erosion Trust
SLR	Sea Level Rise
SLRV	NOAA’s Sea Level Rise Viewer
UNESCO	United Nations Educational Science Cultural Organization

1.0 Introduction

Climate change affects human and natural systems on a global scale. The effects of climate change depend on processes and interactions between several factors (i.e. ocean warming, sensitivity of the climate, and the carbon cycle) that are not completely understood and not progressing linearly (Fideicomiso de Conservación de Puerto Rico, 2010.b.). Impacts manifest in both rapid hazards that can inflict a large amount of damage in a short period of time and slow-onset hazards that gradually develop; both pose risks to human and natural systems around the globe (Tompkins & Adger, 2004). Although climate change is a natural phenomenon, human interference through the release of greenhouse gases is causing it to accelerate. Because of this, the magnitude of climate change impacts is expected to increase in the near future (Van Aalst, 2006).

Impacts of climate change including sea level rise (SLR), air temperature increase, increase in frequency and severity of extreme weather events, coastal erosion, and ocean acidification can negatively impact natural systems and infrastructures within them (Ezcurra & Rivera, 2018). Climate change can interfere with an ecosystem's ability to adapt to the effects of extreme weather events. The impacts mentioned above can push an ecosystem past a "threshold," or an irreversible damage point beyond which it can no longer recover (Climate Impacts on Ecosystems, 2017). Globally, the sea level is expected to rise as much as 5.9 feet by 2100 (Ezcurra & Rivera, 2018). Saltwater intrusion into freshwater systems as SLR progresses, as well as global temperature increases will force both plants and animals to adapt (Climate Impacts on Ecosystems, 2017). Migration periods will shift, and species will need to shift their ranges as the natural habitats are altered (NOAA, 2019). In addition to these natural systems, important cultural heritage sites and infrastructures will suffer from direct flood damage and accelerated degradation of building materials (Haugen & Mattsson, 2018). The development of adaptation strategies is necessary to alleviate existing damages and prevent future ones (United States Environmental Protection Agency [U.S. EPA], 2009).

Adaptation strategies from both public and private institutions are crucial to the preservation of protected areas. The Intergovernmental Panel on Climate Change (IPCC), the United Nations Educational Scientific and Cultural Organization (UNESCO), and the International Union for Conservation of Nature (IUCN) provide information on the effects of climate change as well as broad adaptation and mitigation guidelines. Environmental Protection Agency (EPA) has formulated management guidelines that incorporate infrastructure development, zoning, and conservation plans targeting vulnerability related to climate change (Tompkins & Adger, 2004, Ezcurra & Rivera, 2018). The Australian Government has researched the impacts of coastal climate change and implemented the CoastAdapt system, which provides Geographic Information System (GIS) mapping and detailed risk assessment plans (Australian Government Department of the Environment and Energy, 2019). Venice and the Netherlands have also produced management plans to address impacts of climate change in their regions. Applying existing resources from other management plans to all regions is challenging because the effects of climate change and site conditions vary locally. None of the plans we examined focused on the challenges associated with implementing adaptation strategies, and a cost analysis was typically not included. All the components that are needed to develop an effective management plan exist, but they are scattered across various sources.

Climate change adaptation strategies have been implemented in other areas, but efforts have been limited in Puerto Rico. In recent years, the Puerto Rican Climate Change Council has assessed climate change impacts on the island and developed a set of adaptation strategies (Puerto Rican Climate Change Council, 2013). However, even at the local level, the challenges associated with implementing adaptation strategies in protected areas were not considered. This reflects a larger problem with all the management plans discussed above: they are usually focused on developed areas. Our sponsor, Para la Naturaleza (PLN) is a private nonprofit organization that aims to monitor and protect various lands of high ecological value on the island (Para la Naturaleza, Who Are We?, n.d.). Mangrove forests, historic coffee and sugar plantations, aqueduct systems, natural bodies of water, wetlands, and underground caves are just some of the areas that PLN is currently managing (Para la Naturaleza, Protected Areas, n.d.). Unfortunately, PLN's existing management plans currently do not account for climate change impacts, which many of these sites are already being affected by. Most of the necessary components to deliver an effective management plan exist, but they need to be synthesized. None of the management plans we examined focused on the challenges associated with implementing strategies in protected areas. Any strategies that we proposed to PLN are as natural, subtle, and non-invasive to maintain the natural appearance of the protected areas; many traditional strategies were not applicable. An additional factor that has often been overlooked in past work is a cost analysis of implementing these strategies.

The overall goal of this project was to provide recommendations for climate change adaptation strategies that can be incorporated into the management plans for protected areas monitored by PLN. This was accomplished by first analyzing site maps and existing management plans. We also utilized GIS software to project the impacts of climate change over time. Interviews and site visits were conducted to gain a better understanding of the cultural, environmental, tourism, and infrastructural value of each site. With all this information in mind, critical areas were identified by prioritizing based on importance and vulnerability. Our team then recommended potential adaptation strategies to our sponsor, along with a cost analysis for each strategy. Our group aimed to provide the least invasive methods to maintain the site's aesthetics. We recognize that climate change is a global issue extending far beyond Puerto Rico. Therefore, we aimed to create a comprehensive process for recommending climate change adaptation strategies that can be extended other regions around the world.

2.0 Background

Climate change impacts are becoming more severe, especially in coastal regions. In this section, we discuss the effects of climate change, how these repercussions can negatively impact natural and built systems, as well as methods that have been used to manage these effects. We then discuss the island of Puerto Rico and the organizations involved in managing climate change there. Finally, we will identify areas in Puerto Rico that may be particularly vulnerable. This background expands upon key points mentioned in the introduction and provides context to understand the threats of climate change and the importance of adaptation.

2.1 Climate Change

Though Earth's climate fluctuates naturally over time, the added impact of human interference causes climate change to progress at a faster rate (Revel, 2014). The accelerated rate of modern climate change is caused by the release of greenhouse gases, deforestation, agriculture, and pollution (Van Aalst, 2006). These all collectively increase the amount of heat from the sun that is trapped within the atmosphere, while reducing the amount of natural greenhouse-gas-sequestering systems. Extreme weather formations caused by the added energy in the atmosphere can increase the frequency and scale of natural disasters, affecting human and natural systems worldwide (Van Aalst, 2006).

The effects of climate change can be broken into two types: rapid- and slow-onset hazards. Both pose risks to human and natural systems around the globe (Tompkins & Adger, 2004). Rapid-onset hazards are visibly affecting global communities through unusual seasonal climate variability, coastal erosion, increased frequency of extreme weather events, and rapid climate changes which cause catastrophic shifts in ecosystems (Tompkins & Adger, 2004). As temperatures rise due to climate change, an increase in frequency and severity of extreme weather events such as hurricanes, monsoons, and droughts is being observed (Revel, 2014). Van Aalst documented correlations between climate change and extreme weather patterns, and indicated a 0.6 °C increase in mean global temperatures over the last century (2006). This rise in temperature has been linked to an increase in global extreme weather events such as the European heatwave of 2003, extreme hurricanes in 2004 and 2005 in the Atlantic, and inland flooding of central Britain (Van Aalst, 2006). These extreme weather events will continue to cause more damage to human systems, economy, and infrastructure than in the past.

The second type of climate change effects are slow-onset impacts, including sea level rise and ocean acidification (Diaz & Jacobs, 2015). These effects take more time to manifest and destructively impact coastal regions. As the sea level rises, it will cause direct flood damage and provide a base for storm surges to affect areas that are farther inland. This will present a risk to human and natural systems that are not adapted to coastal wear. (Australian Government Department of the Environment and Energy, 2019). The ocean is a carbon sink that absorbs about 30% of the carbon dioxide that is released into the atmosphere from the burning of fossil fuels (World Wildlife Foundation, 2017). As a result, the ocean is becoming more acidic, affecting marine life. Looking ahead to the next 30-50 years, these effects will begin to have much more destructive impacts (Diaz & Jacobs, 2015).

2.1.1 Impact of Climate Change on Ecosystems

Ecosystems are being forced to adapt to the effects of climate change as average temperatures increase, sea level rises, and extreme weather events increase in frequency and intensity. Because many of these impacts are related to the ocean, coastal zones are especially vulnerable to the impacts of climate change (Greenfieldboyce, 2007). The accelerated effects of climate change are interfering with ecosystems' abilities to adapt to the surrounding environment (Gould et al., 2018). Coral reefs are an example of an ecosystem struggling to adjust to the impacts of climate change. Ocean acidification combined with global temperature increases are increasing the frequency of coral bleaching events. There has been an average global temperature increase of 1.5 ^{o}C over the past 100 years. (Climate Impacts on Ecosystems, 2017). At a warming of 2 °C virtually all coral reefs will be lost (World Wildlife Foundation, 2017). While coral can adapt to occasional shifts in temperature, these prolonged warmings will lead to permanent death of these important natural organisms. Once the coral is no longer offering protection, a negative feedback loop begins in which the increased wave action onshore will damage other natural features that offer protection, such as mangroves and seagrass. Once these features are destroyed, areas further inland become vulnerable (Gould et al., 2018).

Coastal mangrove forests may mitigate the impacts of climate change naturally in coastal areas. Mangrove forests have the ability to gradually create a buffer between sea and land, even when the area is subjected to potential SLR of up to 0.5 millimeters per year (Mangroves help protect against sea level rise, 2015). Even after SLR, mangroves have shown an enhanced ability to maintain an elevation in the upper intertidal zone (Mangroves help protect against sea level rise, 2015). Though mangroves are specially adapted to high salinities and temperatures, tidal changes, and anaerobic sediments, these same adaptations can also make them somewhat vulnerable to natural stresses (Impacts on Mangroves, 2018). Their aerial roots are especially sensitive to long periods of flooding. If these specialized roots are covered for extended periods of time by sediments or water, the mangroves may die due to a lack of oxygen reaching the plant tissues (Impacts on Mangroves, 2018).

As SLR progresses, saltwater will enter freshwater systems (Climate Impacts on Ecosystems, 2017). This, along with global temperature increases, can force species to relocate or deteriorate (IPCC, 2007). This has the potential to impact the food chain by removing key predators and/or prey from certain areas. (Climate Impacts on Ecosystems, 2017). In both terrestrial and aquatic ecosystems, animals and plants are being forced to move to higher elevations at an average rate of 36 feet per decade and moving north at a rate of 10.5 miles per decade. Species can be forced into less survivable habitats or eventually run out of natural areas to relocate to (Climate Impacts on Ecosystems, 2017). The recent behavior of many species indicates that global warming is affecting other natural events in biological systems. This includes the earlier timing of spring events (i.e. leaf-unfolding, bird migration, and egg-laying) (IPCC, 2007). Milder winters are encouraging species to migrate earlier, and they can experience a shortage of food if they arrive to their destination before food is available (Climate Impacts on Ecosystems, 2017). Many of the climate change effects that are impacting natural systems can also be detrimental to infrastructure and other human systems.

2.1.2 Impacts of Climate Change on Cultural Heritage Sites and Built Infrastructure

On a global scale, UNESCO selects areas and landmarks to become World Heritage Sites. The identification of these sites is important to raise awareness about the effects of climate change internationally and encourage preservation of our world's most sensitive sites (Haugen &

Mattsson, 2011). There are three main classifications of World Heritage Sites: natural, cultural, and mixed-use. Natural heritage sites are typically national parks or landmarks that display excellent natural beauty. Many natural heritage sites around the world are already being impacted by the climate change effects discussed above. Cultural heritage sites refer to the historically built environment, and these sites are also vulnerable to climate change impacts. Mixed-use sites contain elements of both classifications (Von Schorlemer & Maus, 2014).

Climate change has been listed as one of the biggest dangers to heritage sites by the World Heritage Committee since 2005 (Von Schorlemer & Maus, 2014). Any change in the natural landscape will have a direct impact on the condition of a natural heritage site (Gould et al., 2018). The impacts of climate change are also important when considering cultural heritage sites because they are non-renewable resources (Haugen & Mattsson, 2018). If a normal building, like school or government office, were damaged, repairs could be made to restore the facility's functionality. Cultural heritage sites hold centuries of history. The moment they are damaged, it is impossible to restore them to their original condition. When structures were initially built, the designers had a specific climate in mind. As the climate changes, these buildings are not able to sustain the new elemental challenges they are exposed to (Von Schorlermer & Maus, 2014).

Both historically built infrastructure and modern infrastructure (i.e. roads, drainage systems, and utilities) are vulnerable to climate change impacts. Valuable historical and cultural sites in coastal zones are at risk of sea water inundation and structural damage as the sea level rises and extreme weather events become more frequent and severe (Ezcurra & Rivera, 2018). SLR will also increase exposure of coastal infrastructures and cause salt crystallization in porous walls and loss of foundational stability (Von Schorlermer & Maus, 2014). Infrastructures and buildings with stonework constructions (i.e. limestone or mortar) and those made of metal will degrade more rapidly from increasingly acidified ocean water (Ezcurra & Rivera, 2018). Air pollution can also contribute to the soiling of stone, metal corrosion, and limestone recession (Von Schorlermer & Maus, 2014). An increase in global temperatures corresponds to a decrease in relative humidity. This can lead to cracking and thermal stresses, especially in wooden structures (Ezcurra & Rivera, 2018). Coastal erosion due to rising tidelines will result in destructive impacts of roads and other man-made infrastructure (Van Aalst, 2006). Erosion has been recorded at rates of one meter per year in coastal areas, and it can be far greater in a shorter period during extreme weather events (Ezcurra and Rivera, 2018)

2.2 Previous Research and Adaptation Strategies

As a problem that affects all regions, many organizations and nations have created management plans to adapt coastal regions to climate change. One such organization is the IPCC who created a standardized set of guidelines to protect infrastructure. Their main goal is to promote advanced development, equity, and sustainability through a report consisting of adaptation strategies and the associated social implications (Tompkins & Adger, 2004). The IPCC suggests that with proper urban planning and zoning, climate change could have less of an impact on infrastructure (Tompkins & Adger, 2004). They also claim that the vulnerabilities caused by climate change can be overcome through, "the ability of the system to adjust to climate change, moderate potential damages, take advantage of potential opportunities, or cope with the consequences" (U.S. EPA, 2009).

The IUCN provides public, private and non-governmental organizations with the skills and resources to promote human progress, economic development and nature conservation (International Union for Conservation of Nature, 2019). The *Adapting to Climate Change* report by the IUCN, provides an outline to effectively maintain sites impacted by climate change through different forms of assessment, prioritization, implementation, and future monitoring of the site (Gross, Watson, Welling & Woodley, 2016). Although this serves as a descriptive guideline for adaptation strategies, there are no specific climate change adaptation strategies included in the document.

A basis for adaptation strategies can be found in a UNESCO report, which combats the vulnerabilities associated with climate change (Ezcurra & Rivera, 2018). Their report highlighted the importance of an adaptive management plan, in which procedures can be re-evaluated and adjusted. This organization claims that mapping and monitoring certain regions is necessary to determine the vulnerability of different sites affected by climate change (Ezcurra & Rivera, 2018). The Environmental Protection Agency (EPA) has also created a report that highlights specific adaptation strategies that can be used in coastal regions. The strategies target the effects of sea level rise, changes in precipitation, higher ocean temperatures, an increase in storm intensity, and altering seasonal changes (U.S. EPA, 2009). Examples from this adaptation strategy include establishing rolling easements, planting submerged aquatic vegetation to control erosion, and designing new coastal drainage system (U.S. EPA, 2009). A full list of adaptation strategies is shown in Appendix A.

Although these organizations have proposed management plans that are useful for their particular needs, they are insufficient. Each plan only contains a portion of the necessary components of a successful management plan; an ideal plan would synthesize all necessary components in detail, including an assessment protocol, prioritization method, adaptation techniques, and aspects of cost feasibility (Ezcurra & Rivera, 2018). This information is crucial to identify the sites in need of attention and proper implementation of adaptation strategies. Unfortunately, the management plans mentioned above are either outdated, inaccessible, lack explicit processes, are difficult to expand to other locations, or do not focus on the implementation of strategies in natural areas. Most plans focused on protecting infrastructure in developed areas and do not consider the impact that certain adaptations may have on sensitive ecosystems. Overall, site specificity limits these management plans to isolated regions, restricting future utilization in other places (Tompkins & Adger, 2004).

2.2.1 Approaches and Management Plans

Many regions have started to utilize new approaches and management plans to counteract the challenges that disturb their coastal areas, including the impacts on infrastructure. The Australian Government created the CoastAdapt system in response to climate change. CoastAdapt assesses the impacts of climate change and provides management plans that can be easily followed by the general public (Australian Government Department of the Environment and Energy, 2019). One of the features of this system is the Coastal Climate Adaptation Decision Support (C-CADS), which provides a step-by-step process for assessing different risk factors (NCCARF, 2019). To address the uncertainties of adaptation strategies, this method allows for trial-and-error to eliminate the chance of being locked into a specific plan, which can be ineffective and a financial burden. This shows all facets of the adaptation strategy, including the risks associated with it. C-CADS is useful for determining long-term management plans when there is sufficient research conducted on the strategies (NCCARF, 2019). A concept map of this iterative process is shown in Figure 1 (NCCARF, 2019).

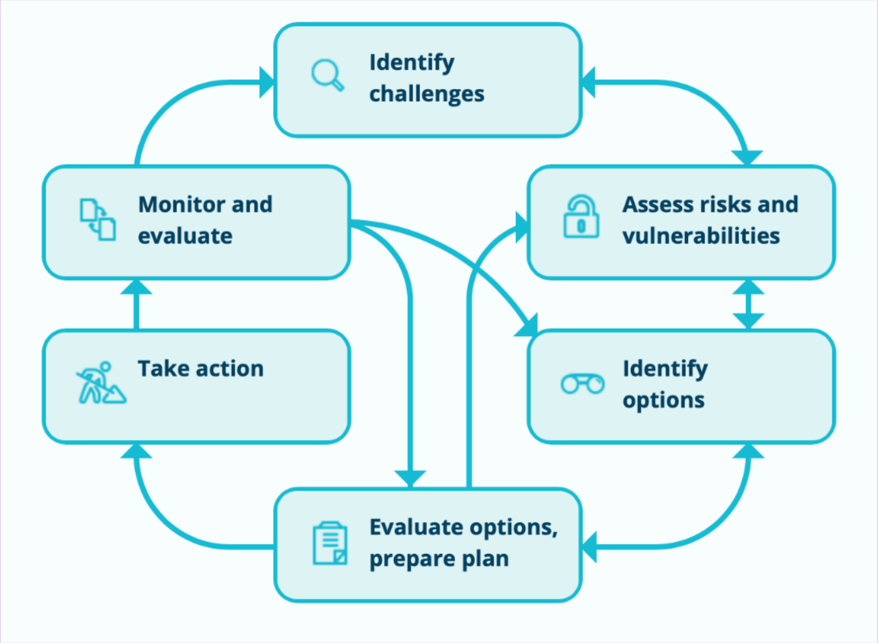


Figure 1. Coastal Climate Adaptation Decision Support Map

Management plans have also been produced to combat SLR in the Venetian Lagoon (Munaretto, Vellinga & Tobi, 2012). Rising waters are impacting surrounding regions, with particular risk to the infrastructure. The plan focuses on the projected erosion, tidal floods, and destruction of infrastructure resulting from a higher sea level (Munaretto, Vellinga & Tobi, 2012). Some of the main components of their adaptation strategies are the protection of urban regions from rising water, alleviation of the effects of coastal erosion and natural disasters, and socioeconomic development in Venice (Munaretto, Vellinga & Tobi, 2012). This management plan mainly considers the degradation of infrastructure, as this is a major impact of climate change in the region.

The Netherlands has attempted to implement strategies to reduce the impacts of climate change through an adaptation ranking system. The scoring process is based on the following criteria: the gross benefits of the solution, the urgency of the problem, the likelihood of success, the co-benefits to surrounding areas, and the effects on climate change adaptation (Bruin et al., 2009). By assigning values to the strategies, they can determine the most urgent issues and which methods will be the most successful. They have composed a list of adaptation alternatives and general estimates of implementation. This management plan looks at aspects of agriculture, water, energy, transport, healthcare, tourism, and infrastructure as shown in Appendix B.1 (Bruin et al., 2009).

The housing and infrastructure section of the Netherlands management plan features several highly-ranked strategies, suggesting that these problem areas need to be prioritized. Water management systems and spatial capacity were two of the higher ranked techniques, specifically trying to avoid the heat island effect (Bruin et al., 2009). The heat island effect occurs in built-up urban regions where the temperature is greater than surrounding areas due to the thermal attraction of the infrastructure (Environmental Protection Agency, 2018). Therefore, strategic development could potentially reduce the risk of temperature increase in urban areas (Bruin et al., 2009). The Netherlands adaptation ranking system also considers the financial aspect of climate change adaptation. Some specific costs of implementation, such as improving dikes and installing a sea wall can be shown in Appendix B.2. Existing adaptation strategies come at a high cost, which may not be feasible in less developed countries. The strengths and weaknesses of each management plan discussed in this section are described in Table 1. Countries around the world have worked to resolve some of the issues with UNESCO and IPCC guidelines by developing plans that work for their specific regions.

Table 1
Strengths and Weaknesses of Existing Climate Change Management Plans

	Strength	Weakness
IPCC	• Assessment processes • Broad adaptation techniques	• Lacks cost of implementation • Outdated • Information inaccessible
EPA	• Relative costs • Broad adaptation techniques	• No info on prioritization or assessment • No explicit details of implementation
UNESCO	• Background on climate change • Risk to cultural heritage sites	• Lack of accessibility and cost feasibility • Used specifically for cultural heritage sites
International Union for Conservation of Nature	• Assessment and prioritization protocol • Tools for implementation and future monitoring	• Does not include specific adaptation strategies
CoastAdapt	• Assessment protocol • Adaptation strategies • GIS Mapping • Easily accessible	• Does not discuss cost analysis
Netherlands Ranking System	• Discusses and ranks adaptation methods • Information on relative costs	• Lacks specific implementation costs • Lacks details of prioritization
Venice	• Information on specific risks to infrastructure	• Only discusses risks of rising sea level

	• Detailed strategies to combat these risks	• Does not include aspects of cost feasibility

2.2.2 Types of Adaptation Strategies

Organizations developing management plans that supplement the work done by UNESCO and the IPCC have found that the most promising plans for adaptation are location-based combinations of hard and soft adaptation strategies (U.S. EPA, 2009). Hard methods, also known as armoring, are implemented where important infrastructure on the coastline is at risk. Armoring includes placement of fixed barriers or structures such as dikes, which are typically made of concrete or stone. These structures protect coastal roads and buildings from inundation by water (Titus, 2011). Protecting foundations of buildings and other infrastructure from sea level rise and flooding is key for maintaining the durability of these structures. Though armoring can be effective and necessary for some locations, it typically requires more expenditure of time and manpower for maintenance and can be detrimental to the environment (Titus, 2011). Creating dikes around everything could be as destructive as the changing climate itself, as this would destroy coastal habitats (Cambers, n.d.).

Soft methods tend to be less invasive to the environment, preventing erosion through the use of materials like those already found in a given location (Titus, 2011). The approach of rolling easements accepts that preventing water rise is relatively futile but provides a framework for the use and adaptation of coastal areas while available. Rolling easements make it possible to use coastal resources while still preserving the coastline (Cambers, n.d.). This method is often cost effective, because more revenue can be obtained through accessible coastlines, and less maintenance is required than dikes and beach nourishment. Previous research has indicated that coastal areas, particularly natural protected areas, tend to benefit more from soft methods. To an extent, natural areas can adapt without assistance. Because of this, facilitating retreat may be more cost effective in the long term than attempting to protect coastal infrastructure. However, this must be assessed for each site since it is dependent on the economic and cultural value (U.S. EPA, 2009).

Puerto Rico’s unstable economy may make it challenging to implement some of the strategies listed above (Carubba et al., 2013). Because of this, a cost analysis is required to prepare for the expense of these strategies. Existing management plans from both international, national, and local organizations consistently fail to address aspects of cost feasibility. The components required to deliver an effective management plan exist, but they need to be synthesized into a single accessible document. In addition, the existing management plans focused on developed areas and did not consider the challenges associated with implementing adaptation strategies in protected natural areas. To date, there have been limited efforts by groups in Puerto Rico to research and implement climate change adaptation strategies.

2.3 Major Stakeholders in Puerto Rico

Puerto Rico is located between the Caribbean Sea and the Atlantic Ocean, about 1,000 miles to the south of Miami, Florida. It has a total area of approximately 3,500 square miles. There are several small islands off the coast, the largest being Vieques and Culebra directly to the East (Puerto Rico, n.d.). Like most small islands, Puerto Rico has a large amount of coastal zone relative to total land area. (Gould et al., 2018). Forty-four of Puerto Rico’s 78 municipalities are coastal or insular (Carrubba et al., 2013). The southern and eastern coasts are the most vulnerable to storm surges because of shallow coastlines and proximity to hurricane paths (Carrubba et al., 2013). With the recent developments of Hurricane Maria, there were approximately 80 billion dollars in damage (Talty, 2018). There are several different groups involved in efforts to manage the impacts of climate change on the island.

In 2010, the Puerto Rican Climate Change Council (PRCCC) was formed to coordinate efforts involving the assessment of climate change risks and proposal of adaptation strategies (Puerto Rican Climate Change Council, 2013). The organization's first publication arrived in 2013, when the PRCCC published an extensive report titled *Puerto Rico's State of the Climate.* This document discussed the impacts of climate change, future projections, gaps in knowledge, and vulnerable systems in Puerto Rico. An Adaptation Strategies document followed a few years later that contained potential climate change adaptation techniques to address the risks that are discussed in the first report (Puerto Rican Climate Change Council, 2015).

The Conservation Trust of Puerto Rico is another major stakeholder involved in the protection of vulnerable areas. This private, nonprofit organization manages many environmentally sensitive areas in Puerto Rico (Conservation Trust of Puerto Rico, 2019). The Conservation Trust also manages a smaller branch, PLN, a nonprofit organization based in San Juan. Their mission is to involve surrounding communities through volunteering and educational events to assist with the conservation of different ecosystems and to increase to amount of protected lands in Puerto Rico (Para la Naturaleza, n.d.). PLN has a goal of being able to monitor 33% of the island's historical and ecological sites by the year 2033 with the help of the community and the local government (Para la Naturaleza, 33% by 2033). PLN produces site-specific management plans for each of their protected areas. These plans include historical information, site value, types of habitat, potential threats, and the existing management strategies in place for the site (Fideicomiso de Conservación de Puerto Rico, 2010.a). Although these plans include many strategies to maintain these areas, there is no discussion of site-specific strategies to adapt to climate change. One of these plans, published in 2010, states that climate change is not a common topic in the current plans, but it is likely to become a high priority issue (Fideicomiso de Conservación de Puerto Rico, 2010.b). With updates made to the management plans every 10 years, climate change impacts and adaptation strategies will likely be included in the next revision. Currently, PLN utilizes the IUCN as their standard for any efforts related to climate change adaptation. Their resources include a procedure for addressing different vulnerabilities within a protected area (Gross, Watson, Welling & Woodley, 2016)

Outside of private organizations, the government is attempting to help preserve the island of Puerto Rico. On November 20, 2018, the current Puerto Rican Governor stated that Puerto Rico would start to implement adaptation strategies for climate change and create a more environmentally sustainable island. One specific strategy discussed combating coastal erosion by implementing a reforestation project alongside critical coastal lands (Puerto Rico at the forefront of climate resiliency, 2018). The local government has also been using the Puerto Rican Tourism Company, a government run organization, to help increase tourism and bring revenue to the island to boost the economy after the damages caused by Hurricane Maria (Caribbean Business, 2018; Puerto Rico tourism company, 2019). Efforts by the local government have been assisted using federal funding to aid in relief after Hurricane Maria. The Federal Emergency Management Agency (FEMA) was awarded over five billion dollars by the Federal Government to help rebuild the infrastructure in Puerto Rico. This money was used to help the local government as well as select non-profit private organizations on the island (FEMA, 2018). Compared to the states, territories usually receive a fraction of the funding for relief programs. The damage caused by

Hurricanes Maria and Irma was estimated to be over $94 billion in November of 2017 (Mazzei, 2018). A lot of focus has been given to the entire island of Puerto Rico, but there are areas that need more focus due to their cultural or environmental importance.

2.4 Vulnerable Sites and Infrastructure in Puerto Rico

Although PLN does not manage any officially designated UNESCO Sites, many of their protected areas are considered heritage sites locally (Von Schorlemer & Maus, 2014). There are only approximately 1,000 UNESCO World Heritage Sites in the entire world, indicating that this is a highly selective process. There are likely thousands of other sites not chosen by UNESCO that have local significance (Von Schorlemer & Maus, 2014). Regardless of their designation, all heritage sites are important components of the communities they are located in. In 2015, cultural heritage sites in Puerto Rico brought in $3.44 billion through tourism revenues (Ezcurra and Rivera, 2018). These sites can also unite local populations by providing a sense of social identity and common purpose (Von Schorlemer & Maus, 2014). These tangible sites create a link between abstract climate change statistics that scientists talk about and real impacts on a local level (Ezcurra & Rivera, 2018). People are more likely to get involved in preservation efforts if they see damages in their community, rather than hearing about temperature changes on the scale of one tenth of a degree per year. In addition to these cultural heritage sites, the island contains a vast wealth of natural resources that must be protected due to their ecological significance. In some cases, cultural heritage sites are located within ecologically sensitive areas, with natural and built systems coexisting (Von Schorlemer & Maus, 2014).

PLN manages many different ecologically valuable lands in Puerto Rico. They selected two of these areas to be the focus of our project (Para la Naturaleza, Who Are We?, n.d.). The first site is Las Cabezas de San Juan Nature Reserve, a 316-acre natural reserve located on the northeastern most tip of the island (Goethals, 1991). This area would likely be considered mixed use by UNESCO and their World Heritage Designations, since it contains both natural and built systems that have some level of importance. The centerpiece of the reserve is El Faro, one of the oldest and best preserved lighthouses on the island (Fideicomiso de Conservación de Puerto Rico, 2010.b). Including the lighthouse, several sites around the reserve have archaeological value, where indigenous artifacts have been discovered (Fideicomiso de Conservación de Puerto Rico, 2010.b). As of 2010, 30,000 to 40,000 people visit the area annually (Fideicomiso de Conservación de Puerto Rico, 2010.b). The recreational value of the reserve is excellent, with activities such as fishing, surfing, snorkeling, and walking trails (Fideicomiso de Conservación de Puerto Rico, 2010.b). Las Cabezas de San Juan Nature Reserve is also home to 11 ecosystems, and over 800 species (Fideicomiso de Conservación de Puerto Rico, 2010.b). 29.4% of the land is covered by wetlands or mangroves that provide habitats for many bird species (Fideicomiso de Conservación de Puerto Rico, 2010.b). Forests, mangroves, a rare bioluminescent lagoon, beaches, cliffs, and coral reefs are home to an abundance of plant and animal species, several of which are endangered (Goethals, 1991). The reserve has been recognized by the Puerto Rican Department of Natural Resources as one of the island’s critical wildlife areas (Weaver, Cole Rivera, & Ramirez, 1999).

The second site, Área Natural Protegida Medio Mundo y Daguao, is composed of 17 different plots of land and is the largest protected area that PLN manages (Fideicomiso de Conservación de Puerto Rico, 2010.a). This protected area was historically part of the Roosevelt Roads Naval Base commissioned in 1943. It contains the second largest mangrove forest in Puerto Rico, beaches, seagrass beds, coral reefs, and rocky coasts, which are home to more than 616 species of flora and fauna. This includes 123 species of fish, 128 species of birds, and 288 species of plants (Fideicomiso de Conservación de Puerto Rico, 2010.a). The region is home to 26 rare, vulnerable, or endangered species, such as the Antillean Manatee, Ladybug, Puerto Rican Boa, and Sea Turtle (Fideicomiso de Conservación de Puerto Rico, 2010.a). The natural preserve provides many natural and cultural attractions, which provide regional importance through tourism, educational opportunities, and scientific research. Recreational value is found through the walking trails, park areas, biking trails, beaches, golf course, diving and snorkeling opportunities, fishing, camping spots, and historical site visits (Fideicomiso de Conservación de Puerto Rico, 2010.a). Área Natural Protegida Medio Mundo y Daguao is also valued for its natural resources, including commercial fishing and deposits of different minerals and soils (Fideicomiso de Conservación de Puerto Rico, 2010.a).

Even when considering as few as two sites, it is clear that each area has its own characteristics, history, and needs. Because of this, it is important to develop a plan that is both broadly applicable but also personalizable. By using existing methods as a framework, we were able to develop a method to assess existing conditions, prioritize sites and provide recommendations to protect these important areas. Our methodology can be extended to other vulnerable areas under the management of PLN, as well as other regions that may be in need of climate change adaptation strategies.

3.0 Methodology

The goal of our project was to provide PLN with climate change adaptation strategies for their protected areas, with a focus on infrastructure and cultural heritage sites. These strategies will augment existing management plans, and the assessment and prioritization methodology we have developed can be extended beyond the reach of our project. To achieve this goal, our team developed the following objectives:

1. Assess the two sites selected by PLN to gauge the effects of climate change on existing infrastructure and natural systems
2. Prioritize the most critical areas, based on importance and vulnerability to climate change impacts
3. Identify potential adaptation strategies and perform a cost analysis

3.1 Assessment of Two Protected Areas

To complete the first objective, we utilized software such as The Interactive Map of Puerto Rico (MIPR), the National Oceanic and Atmospheric Administration (NOAA) Sea Level Rise Viewer (SLRV), and ImageJ. We also examined management plans, held interviews with PLN employees, and visited each site to assess the existing conditions of the two protected areas selected by PLN. Table 2 summarizes the strategies we utilized to assess the varying impacts of climate change.

Table 2

Strategies to Assess Impacts of Climate Change

Specific Impacts	Evaluation Methods
Sea Level Rise	• NOAA's Sea Level Rise Viewer (SLRV) • Interactive Map of Puerto Rico (MIPR) • ImageJ
Flooding	• Existing maps • Interviews with PLN employees and workers on each site • MIPR topography and floodplain layers • ImageJ
Coastal Erosion	• The Conservation Trust of Puerto Rico Management Plans • Interviews with PLN employees and workers on each site • Analyzing photos from site visits
Degradation of Infrastructure	• The Conservation Trust of Puerto Rico Management Plans • Interviews with PLN employees

3.1.1 Utilization of Online Software

The first step of our assessment was to use software to examine the two protected areas selected by PLN. The locations we observed were Las Cabezas de San Juan Nature Reserve and

Área Natural Protegida Medio Mundo y Daguao. We utilized NOAA's SLRV to identify regions most susceptible to rising waters (NOAA Office for Coastal Management, n.d.). This online program allowed us to approximate the risks associated with each of the sites. The system captures the rising waters by one-foot increments, and as the depth increases, more of the island is submerged. We stored these images in our Google Drive and used them to show the regions most at risk. NOAA warns that the, "...data, maps, and information provided should be used only as a screening-level tool..." (NOAA Office for Coastal Management, n.d.). Because of this, we used this information as a preliminary data collection method that was later supported by more reliable software and in person site visits.

The Government of Puerto Rico's MIPR online GIS was used to locate the chosen sites, identify surrounding structures or ecosystems, and determine their proximity to the ocean or floodplains (The Government of Puerto Rico, 2015). This was particularly useful when looking at strategies to combat coastal climate change and flooding. We used the software to identify the location of floodplains within the sites, as well as any loss of land due to sea level rise. Through GIS mapping, we were able to identify the areas that have already been affected by climate change impacts and those that are projected to be in the future. The storage of this content consisted of screen-capturing maps to analyze and use as evidence for our recommendations. These images were stored in our existing Google Drive. The MIPR data was compared with the NOAA data, and any similarities or differences between the projections were noted. If any discrepancies were observed, we deferred to the MIPR data because of NOAA's warning mentioned above. Once we had obtained all the images, we used area measurement tools within ImageJ software to analyze the images (Rashand, 2018). This provided us with approximate percentage of each protected area that would be inundated at increments of one, three, and six feet of SLR since these were the increments used in the MIPR. This information was used in the prioritization of vulnerable areas within the sites.

3.1.2 Evaluation of Existing Conditions

Management plans provided by the Conservation Trust of Puerto Rico also aided in the creation of adaptation strategies. These were helpful in classifying the scope of adaptation strategies necessary for each site, as some required plans for different systems (National Park Service, 2016). The management plan for each site were read and the information was extracted and coded into three groups: site importance, risks and threats, and current management strategies. All this information was then synthesized into several paragraphs that summarize the key information about each site.

In addition, the conditions of the sites were further evaluated through informal interviews with representatives from PLN. We separated each interview within a Google Document and used content analysis to highlight the trends in the data. Content analysis is a research tool that identifies certain words, phrases, and themes within qualitative data to understand the meaning or frequency of the information (Columbia University Mailman School of Public Health, n.d.).

We also conducted interviews, which were piloted with a PLN employee by verbally running through the questions and asking how they would answer and if they noticed any ambiguity. If our intention for how a question would be interpreted did not match their perception of the question, then we made alterations accordingly. The interviews were conducted as a discussion with PLN employees to gain a better understanding of PLN's current efforts to adapt to climate change. We used the same basic set of questions to guide each interview. However, we adapted the questions as we proceeded through the interviews since each person's role was different. Individuals that were interviewed held roles including Facilities Coordinator, Environmental Interpreter, Regional Superintendent, Environmental Policy and Government Relations Coordinator, and Production and Planting Manager. These interviews were all conducted in English and each took approximately 45 minutes to one hour to complete. The data from these interviews was collected using handwritten notes and later synthesized on the computer and recorded in our Google Drive. This was helpful when prioritizing the aspects of each site that needed to be addressed based on importance and vulnerability. The questions for the PLN employee interviews can be found in Appendix C.

Maps of each site were also provided during the interviews. This gave interviewees a chance to identify specific areas that were being impacted by climate change within Área Natural Protegida Medio Mundo y Daguao and Las Cabezas de San Juan Nature Reserve. This method was inspired by a study of conflict potential in a coastal environment using participatory mapping (Moore, Brown, Kobryn, & Strickland-Munro, 2017). This introduced social components to the project, where subjects identified coastal regions that they believed were at risk (Moore, Brown, Kobryn, & Strickland-Munro, 2017). This was similar to how we utilized maps during the interviews, as participants located areas that were vulnerable or important. The maps that we used can be found in Appendix D (Brian, 2013; Fideicomiso de Conservación de Puerto Rico, 2010). This information supplemented the MIPR and NOAA SLRV data to accurately identify the areas within each of the sites and allowed us to include the perception of local experts. This data was combined with the background research and analyzed during the prioritization objective. Any information from the interviews that was related to the importance or vulnerability of each site has been incorporated into the results section.

Additionally, we visited Las Cabezas de San Juan and Área Natural Protegida Medio Mundo y Daguao to gather more information on the current conditions of each area. This was accomplished by taking photos of each of the sites to show any current impacts of climate change or any areas that may be at risk. A similar method was utilized in a scientific study that focused on landscape character assessment using photographs to identify the relationship between landscape and roads (Martin, Ortega, Otero & Arse, 2016). In this case study, photography was utilized in addition to GIS mapping to convey the quality of the landscapes for assessments (Martin, Ortega, Otero & Arse, 2016). This identification method provided visual evidence to further support the claims made from the GIS data and interviews (Martin, Ortega, Otero & Arse, 2016). We worked in teams of two to complete this task. Two group members took the photographs, while the others took notes to identify the location of the photo, the purpose of the photo, and any other relevant information. This method was helpful, as it provides visual representations of the climate change impacts we hoped to address within the adaptation strategies. It also showed some of the damages caused by climate change, especially when we looked at degradation to infrastructure and coastal erosion. While on site, we focused our photographs on the following:

- Features that we indicated as potentially valuable through our research and assessment (Cultural, Ecological, Infrastructural, and/or Tourism Value)
- Areas that look to be the most at risk from the MIPR projections
- Any visible signs of damage or areas affected by climate change, such as signs of erosion or flooding

Following the site visits, the photos were stored in a folder on the Google Drive. The hand-written notes were typed and then stored in a Google Document with each photo that was taken. This was used as evidence and qualitative data to show the impacts of climate change at each of the protected areas.

3.2 Prioritization of Most Susceptible Areas

After assessing the current state of the two locations managed by PLN, we prioritized critical areas within the sites. Before discussing methods of prioritization that are specifically relevant to this project, the Eisenhower Matrix provided an idea for the principles that can act as a framework for all prioritization activities. Made famous by U.S. President Dwight D. Eisenhower, the matrix acts as a guide for prioritizing tasks by considering two parameters: importance and urgency. Tasks that are determined to be both important and urgent are completed first (Nguyen, 2012). In order to effectively prioritize our sites, it was necessary to further define a set of parameters and a system that would be applicable for this project. In the context of this project, the "urgency" parameter of the Eisenhower Matrix is replaced by vulnerability. The vulnerability of the sites was based on information that we gathered from Section 3.1. This section includes the use of GIS mapping, interviews with PLN employees, and in person site visits. The importance parameter was further refined to assess the value of each area based on several factors. Table 3 provides details on the prioritization factors that were considered. With these parameters in mind, we were able to identify priority areas as those that had both high vulnerability and high importance.

Table 3
Prioritization Factors

Category	Factors
Vulnerability	• Areas that GIS Data indicated would be partially/completely inundated as sea level rise progressed, or areas in floodplains • Areas in close proximity to coastline susceptible to coastal erosion • Areas that we saw damage/impacts of climate change • Areas that site employees had told us were damaged or susceptible to damage in the future
Importance	• Cultural Importance - Historical buildings or archaeological sites • Ecological Importance - Habitat for endemic/vulnerable species, biodiversity, and carbon sink effect • Tourism Importance - Area offers educational opportunities to tourists and generates revenue through tourism • Infrastructural Value - Features that facilitate activities within the reserve or support other functions

After analyzing the data from our assessment phase with these parameters in mind, we made a list of the areas to propose adaptation strategies for. The importance and vulnerability of each site were summarized in a table. Following this, we used a procedure from the Minnesota Department of Health to prioritize sites based on cultural, environmental, tourism, and infrastructural importance (Prioritization matrix, n.d.). This allowed us to take qualitative data from the assessment and transfer it into quantitative data. To begin, the four parameters were ranked against each other to develop a weighting system. Then, each area was ranked in terms of the four parameters to develop raw scores. These scores were then weighted and totaled to give the total importance scores. This procedure can be viewed in its entirety in Appendix E.1. To prioritize sites in terms of vulnerability, we developed a point system based on similar vulnerability ranking procedures from the Scottish Coastal Archeological and Problem of Erosion Trust (SCAPE) model and the Swedish Civil Contingencies Agency (Eriksson & Juhl, 2012). Each site could earn a total of nine points based on vulnerability to SLR, coastal erosion, and extreme weather events, as well as FEMA floodplain classifications. A detailed breakdown of this point system can be found in Appendix E.2. By comparing the locations of sites to the SLR projections and floodplain areas from the MIPR, we were able to determine the associated risk. The floodplain classifications were useful because they also considered storm surge effects in coastal areas. Coastal erosion points were awarded based on what we saw on site as well as proximity of areas to the coastline. Areas that are located directly on the coast (i.e. beaches) or located in an exposed area that lacks protection (i.e. El Faro) earned an extra point because of their particular vulnerability to extreme weather events. If these methods were to be extended to other areas, the parameters for both importance and vulnerability could be altered based on the characteristics of the area and the risks it is exposed to. Using the numerical rankings from these two processes, we placed each area on a prioritization matrix. A blank matrix is shown in Figure 2 below. Quadrant one designates areas that are considered critical due to high importance and vulnerability. Quadrant two contains areas that are particularly vulnerable, but not necessarily important. Quadrant three contains areas of high importance that are were determined not to be vulnerable at this time. Quadrant four contains areas that are not particularly important or vulnerable when compared to the others being considered. Efforts should be focused on the quadrant one areas first, and then areas in the other quadrants can be considered in descending numerical order.

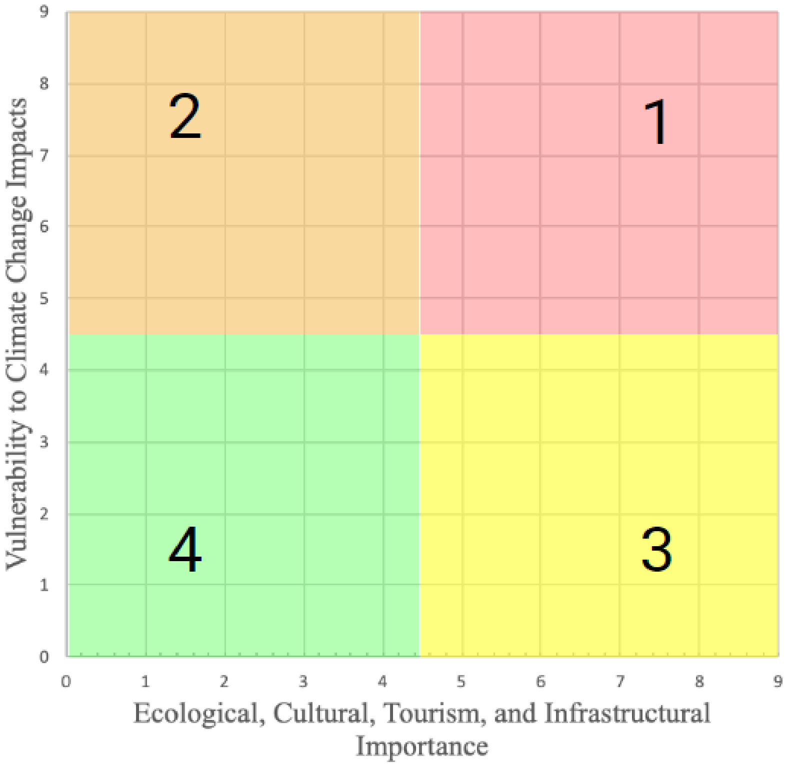


Figure 2. An example of a blank prioritization matrix that was used to rank sites based on importance and vulnerability. Sites that are in quadrant one should be addressed first, and then the other quadrants can be considered in descending numerical order.

3.3 Compilation of Potential Adaptation Strategies and Associated Costs

Due to the variety of climate change impacts, there is no singular adaptation strategy that will work for all associated risks including sea level rise, erosion, and increased storm intensity. The management plans provided to us by PLN did not address the impacts of climate change, so we examined existing management plans from other organizations in order to gain an idea of what had been done. We gathered a variety of strategies from the EPA, CoastAdapt, SCAPE Model, and San Juan Bay Estuary Climate Change Adaptation Plan. In addition to compiling existing strategies, we were able to develop new strategies or make modifications to the existing ones based on information from the interviews we conducted. Finding the most applicable adaptation plans for a given situation is important because, if applied well "...adaptation can help reduce the long-term costs associated with climate change" (Titus, 2011). Unfortunately, adaptation strategies can exacerbate a system's vulnerability to climate change if implemented without careful consideration (U.S. EPA, 2009). With all of this in mind, we created a table of potential adaptation strategies for our protected areas. This table listed potential adaptation strategies grouped by categories such as planting, development/planning, and retreat/avoidance. For each strategy, we listed threats addressed, potential locations for implementation, benefits, and constraints. We chose to mostly include non-invasive strategies in this table to preserve the natural aesthetics of the sites and avoid impacting the ecosystems negatively.

From this table, we synthesized a list of general recommendations organized by the type of habitat or infrastructure that they addressed. These strategies can be extended to other areas within the reserves that we were unable to consider and to other regions being impacted by climate change. We also recommended site specific adaptation strategies for each area that was considered in the prioritization phase. To select strategies from the table for each area, we considered the potential of each strategy to address the risks that are present, past uses in similar locations, suggestions from PLN employees, and any particular constraints of the area. Some areas were limited by remoteness or inaccessibility, and some ecosystems could not retreat inland because they were restricted by infrastructure. Preference was given to strategies that utilized natural materials, especially when these materials were already located on site. Strategies could be disregarded if they were determined to have potential adverse impacts on the area. This included invasive strategies that would disrupt the ecosystems or natural appearance, or strategies that may transfer the impacts elsewhere instead of resolving them. For example, seawalls are intended to minimize coastal erosion and dissipate wave energy. These structures can protect the immediate area at which they are constructed but will redirect currents and waves causing damage other areas and result in loss of coastal habitat (U.S. EPA, 2009).

For each adaptation strategy that we recommended for a specific area, we estimated the costs associated with implementation. We researched past uses of individual strategies to prepare approximate costs of implementation. At a minimum, we were able to provide estimates of material costs. For strategies involving tree planting, we used information provided by PLN's Project Habitat that included total costs for trees, labor, and a five-year monitoring period. For other types of strategies, we also included costs for labor, transportation of materials, and monitoring when information was available. This was limited to select adaptation strategies because these costs will vary locally, and we were unable to accurately estimate the man hours required to implement each strategy. The cost estimates for each strategy were organized in the form of unit cost (i.e. cost per linear foot, cost per square foot, etc.). When applicable, we also estimated the total cost associated with implementing the strategy in a certain area (i.e. total cost to replant a five-meter-wide coastal mangrove belt along the entire length of the Los Machos dirt road). In order to estimate costs, we also provided a more detailed guide for the implementation of many of the adaptation strategies including information such as plant spacing, planting location, stone layer thickness, and levee height.

4.0 Results and Analysis

This chapter includes the results from our work with PLN, a non-profit organization that protects various areas throughout Puerto Rico. The goal of this project was to produce climate change adaptation strategies for PLN to add into their management plans for implementation within their protected areas. In our assessment phase, we determined that Las Cabezas de San Juan Nature Reserve and Área Natural Protegida Medio Mundo y Daguao are important based on factors of ecology, tourism, infrastructure, and history, as well as vulnerable due to the impacts of climate change. With this information in mind, we identified that there are critical areas within each site, including roads, beaches and mangrove forests. Finally, this allowed us to develop a list of adaptation strategies for the critical areas, focusing on non-invasive methods that would protect the aesthetics of the reserves.

4.1 Site Assessment of Protected Areas

The assessment of Las Cabezas de San Juan Nature Reserve and Área Natural Protegida Medio Mundo y Daguao revealed that both protected areas need climate change adaptation strategies. As regions with valuable ecosystems and infrastructure, the protected areas are deemed important based on their ecology, infrastructure, historical features, and tourist attractions. These coastal areas are at great risk due to climate change, especially from SLR, coastal erosion, and storm surges. Unfortunately, the existing management plans do not address climate change related concerns.

Las Cabezas de San Juan Nature Reserve

Las Cabezas de San Juan Nature Reserve is threatened by tourism, irresponsible recreation, urban development, poorly planned infrastructure, greater demand for goods and services, and lack of political support for protection (Fideicomiso de Conservación de Puerto Rico, 2010.b). There are currently strategies in place to address most of these risks, but not climate change. SLR, ocean acidification, and coastal erosion are just a few of the effects of climate change that are currently impacting Las Cabezas de San Juan Nature Reserve that have not been addressed (Fideicomiso de Conservación de Puerto Rico, 2010.b). As of 2010, 44.9% of the reserve is less than 10 meters above sea level. Structures within the reserve that are in danger include the visitor center, administrative office, and paved road because these are very close to sea level (Fideicomiso de Conservación de Puerto Rico, 2010.b).

The MIPR is part of the Puerto Rican Government’s online GIS database. This software serves as visualization tool for identifying different characteristics across the region. Sea level rise projection models from the MIPR suggest that Las Cabezas de San Juan Nature Reserve will be at noticeable risk of partial inundation after as little as one foot of sea level rise. Figure 3 shows GIS images of sea level rise projections in Las Cabezas de San Juan Nature Reserve at various levels. Here, it is apparent that most of the inundation occurs in the zero to three-foot range. Table 4 contains the approximate percentage of land that will be inundated at each increment. These are estimates calculated using ImageJ software and information retrieved from PLN’s management plans. A more precise analysis could be conducted using more sophisticated GIS software such as ArcGIS. For the purpose of this project these estimates are sufficient because they function not as exact figures but as a way to quantify what is shown in the sea level rise images. It should be noted that the Laguna Grande, while shown as being affected by sea level rise, is not included in these calculations because it is already a body of water. Approximately 15% of land will be inundated after one foot of SLR, 30% after three feet of SLR, and 37% after six feet of SLR. While these images are useful to visualize the effects of sea level rise, one aspect that is still unknown is the rate of sea level rise.

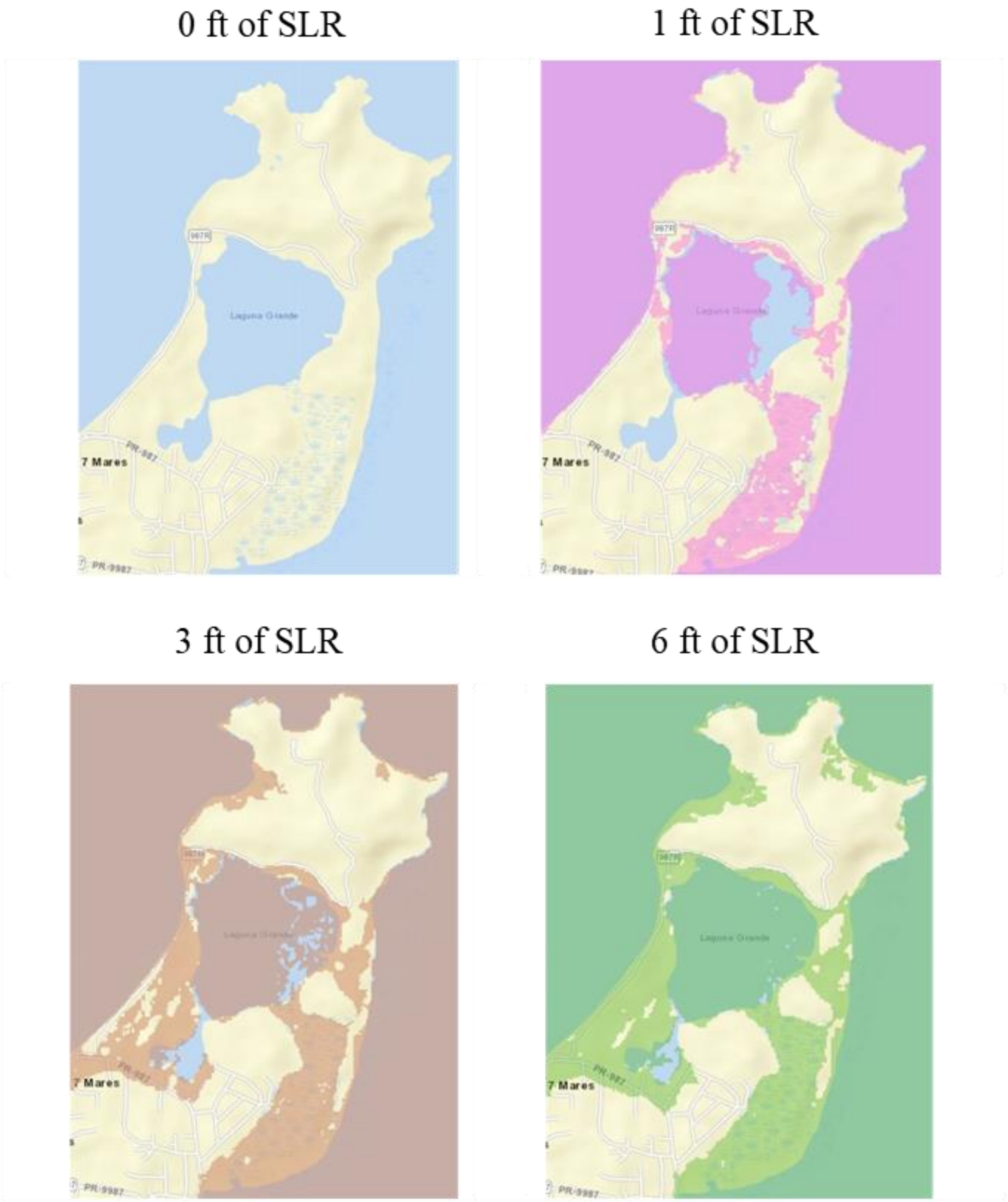


Figure 3. Sea level rise in Las Cabezas de San Juan Nature Reserve.

Table 4
Approximate Flooded Areas for Las Cabezas de San Juan Nature Reserve

	Land Underwater (Acres)	Total Land in Reserve (Acres)	Land Underwater (%)
1 Foot	95	316	15
3 Feet	152	316	30
6 Feet	180	316	37

Through our observations at the sites and information from our tour guide, we determined the sites that are most at risk due to climate change. Factors we were able to observe that indicated a site was at risk included evidence of coastal erosion, proximity to the ocean, and damage from extreme weather events. Damage from the hurricanes typically manifested in large quantities of dead trees and plants, particularly along the coast. Environmental Interpreter Pablo Ponce de León stated that there are not currently any climate change adaptation strategies in place to deal with these effects. The access road is a piece of infrastructure immediately at risk of SLR. The road provides access to the boardwalk, most of the beaches, the lighthouse, and the larger portion of the reserve. This recently paved road lays in the thin strip of land between the ocean and the lagoon. There is a narrow buffer of beach and vegetation protecting the road from erosion and the lagoon from connecting to the ocean. The magnitude of the potential negative impact to the lagoon is unknown. Pablo Ponce de León stated that the lagoon has previously been exposed to a large influx of ocean water during extreme weather events, and there is no known correlation between large amounts of sea water entering the lagoon and the level of bioluminescence (Personal Communication, 2019). If the road was washed out, boats would be needed to ferry tourists and workers to the island which would contain El Faro. Situated on the highest point of the reserve, El Faro is at minimal risk of damage from SLR, coastal erosion, ocean acidification, and any other ocean related effects. This historic structure is still in use as a functional lighthouse and therefore has practical as well as historical value for the site.

The beaches at risk are Playa Jayuya, Playa Lirios, Playa Canalejo, and Seven Seas Beach. All these beaches and the others surrounding Las Cabezas de San Juan are directly at risk of coastal erosion and SLR. These sites have already been observed to be changing within the last several years. Pablo Ponce de León stated that Playa Jayuya had contained dunes five to ten feet higher when he began volunteering there five years ago (Personal Communication, 2019). Five human skeletons and other archaeological items have been found already in this beach adding to the cultural importance (Personal Communication, 2019). The sites identified in Figure 4 are the focus of our project based on their importance and vulnerability as determined by the management plan, MIPR data, and site visit observations. A detailed outline on the various aspects of each site's importance (e.g. cultural, tourism, environmental, and infrastructural) and vulnerability to climate change effects can be found in Section 4.2.

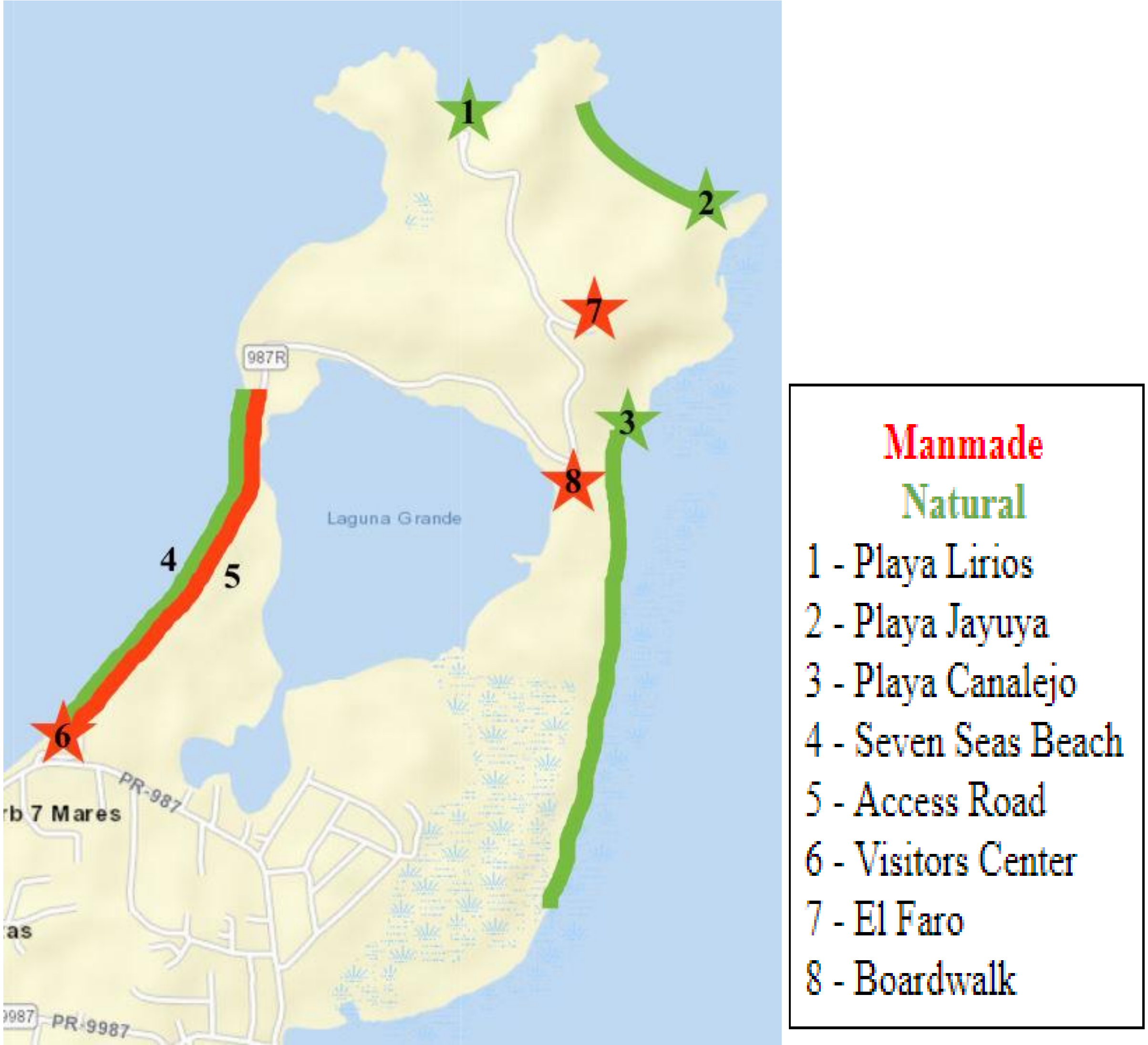


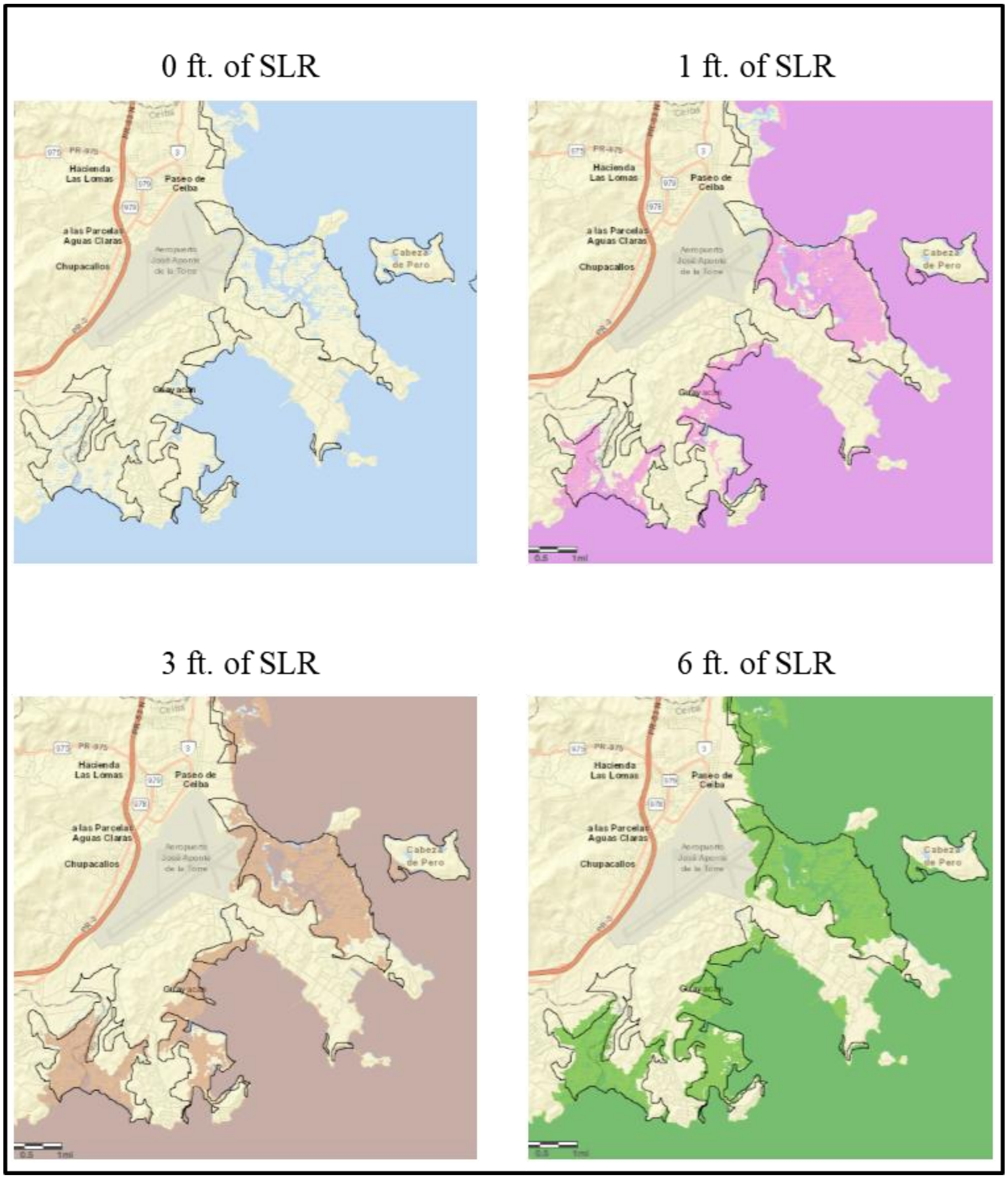
Figure 4. Map showing points of interest in Las Cabezas de San Juan Nature Reserve.

Área Natural Protegida Medio Mundo y Daguao

Because of the extensive size and fragmentation of Área Natural Protegida Medio Mundo y Daguao, it was not possible to assess areas within all sections of the reserve. During the site visit we observed some of the key areas within the reserve likely which had been chosen through the GIS analysis of SLR. The MIPR had indicated that Los Machos, the largest of the 17 sections of land, would be heavily impacted by SLR. For this reason, we focused our efforts in the Los Machos area. The dirt road in this area provides access to the mangrove forest, swamp, and is the same road tours used to access the canals of Los Machos. A metal bridge spans the channel through which ocean water flows into the reserve. The bridge serves as a launching point for kayak tours and access to Punta Medio Mundo (Personal Communication, 2019).

PLN’s management plan describes some of the threats to Área Natural Protegida Medio Mundo y Daguao as “pressures” that could affect and degrade the ecosystem. Pressures that have been noted in the reserve are the loss of biodiversity, disturbance to rare plants and endangered species in the area, degradation of the water quality, destruction of the natural habitat and changes to the structure of the ecosystem (Fideicomiso de Conservación de Puerto Rico, 2010.a). These pressures will affect the reserve’s natural ecosystems and various forms of infrastructure through erosion, advancing of the coast, changes in hydrological flow, and resulting fragmentation (Fideicomiso de Conservación de Puerto Rico, 2010.a).

Similar to Las Cabezas de San Juan Nature Reserve, portions of Área Natural Protegida Medio Mundo y Daguao will be affected by SLR after an inundation of 1 foot. GIS images depicting various SLR scenarios from the MIPR for Área Natural Protegida Medio Mundo y Daguao can be seen in Figure 5. Table 5 contains the estimated percentage of Área Natural Protegida Medio Mundo y Daguao that will be inundated at each increment, as determined by ImageJ software. Approximately 44% of land will be inundated after one foot of SLR, 55% after three feet of SLR, and 62% after six feet of SLR. The areas that will mostly be affected are Los Machos and the Daguao River basin. This is primarily due to the low elevation of these areas as well as their proximity to the coast and various flood plains. One of the issues with using GIS software, as stated by Soledad Gaztambide Arandes, is that the software uses a bathtub model for SLR analysis. This type of model assumes water fills inland to the elevation of the water (Personal Communication, 2019). These “bathtub” models do not take into account changes in coastal geomorphology. These changes can be seen in the accretion rates of sediment around mangroves roots which may raise the level of the land counteracting SLR, while the impacts of coastal erosion which can further the inland progress of water. Though these models are not exact, they are still a useful tool to obtain a good estimate of the impacts of SLR.


0 ft. of SLR

1 ft. of SLR

3 ft. of SLR

6 ft. of SLR

Figure 5. Sea level rise in Área Natural Protegida Medio Mundo y Daguao.

Table 5

Approximate Flooded Areas for Área Natural Protegida Medio Mundo y Daguao

	Land Underwater (Acres)	**Total Land in Reserve (Acres)**	**Land Underwater (%)**
1 Foot	1470	3340	44
3 Feet	1840	3340	55
6 Feet	2070	3340	62

There are elements within Área Natural Protegida Medio Mundo y Daguao that these images suggest are vulnerable to the impacts of SLR. The information from our site visits supported this. One main piece of infrastructure that will be affected is the dirt access road in the Los Machos section. There are parts of the road that are close to the ocean and would be susceptible to flooding due to rain storms and the rising tide. The manager of this reserve, Santiago Oliver Báez said that sometimes the access road is flooded making it unusable. This road is within a few feet of the high tide line in some locations. The edges of this road have been protected by mangroves in the past, but after Hurricane Maria most of the coastal mangroves in that area died. This can be seen in Figure 6. These dead mangroves still provide some protection, while young mangroves on the ocean interface begin to regrow. These dead trees are not as resilient and are far less effective as a buffer if more hurricanes are to arrive within the next few years. Santiago Oliver Báez claims that the trees will regrow with time, but PLN can accelerate this process through volunteer events featuring tree planting (Personal Communication, 2019).

Figure 6. Dead mangroves on the coast in the Los Machos area killed during Hurricane Maria.

With rising sea levels, this bridge may be at risk of foundational instability and faster rates of corrosion than are already observable due to the contact with salt water. At certain times of year, the water level rises over the edge of the bridge already which will be exacerbated by SLR. In Figure 7 the corrosion of the metal in the bridge is noticeable, even though it was replaced approximately eight years ago. Corrosion is visible especially on the nuts, bolts, and connecting hardware. The sticks on the bridge show that the water level had been at least up to the bridge deck at one point. Santiago Oliver Báez stated that he believed metal in close proximity to the ocean had been displaying accelerated corrosion rates over time, likely due to ocean acidification (Personal Communication, 2019).

Figure 7. Bridge in Los Machos showing signs of corrosion and woody debris from flooding.

When asked about changes he had noticed in the environment during his years there, Santiago Oliver Báez said, “wetlands and beaches are already changing, and no program has been established by PLN in the area to protect from climate change” (Personal Communication, 2019). Furthermore, sea turtles may have been impacted by disappearing beaches as they return to the same places to lay eggs. According to Antares Ramos Álvarez, more sargassum has been being washed up on the coastline than in the past; this has been associated with climate change. Sargassum has been observed at both Área Natural Protegida Medio Mundo y Daguao and Las Cabezas de San Juan. In small amounts it brings nutrients, which is good for the surrounding ecology, but when an excess arrives it can be detrimental. The seaweed can stifle sea turtles hatching or laying eggs on usually sandy beaches. The seaweed blooms affect other coastal dependent animals as well but the exact cause of it is still unknown (Personal Communication, 2019). Additionally, the smell and sight pose an issue to tourism companies as it drives away customers. Large amounts of this sargassum were observed covering Medio Mundo beach.

The sites identified in Figure 8 are the focus of our project based on their importance and vulnerability as determined by the management plan, MIPR data, and site visit observations. A detailed outline on the various aspects of each site’s importance (e.g. cultural, tourism, environmental, and infrastructural) and vulnerability to climate change effects can be found in Section 4.2.

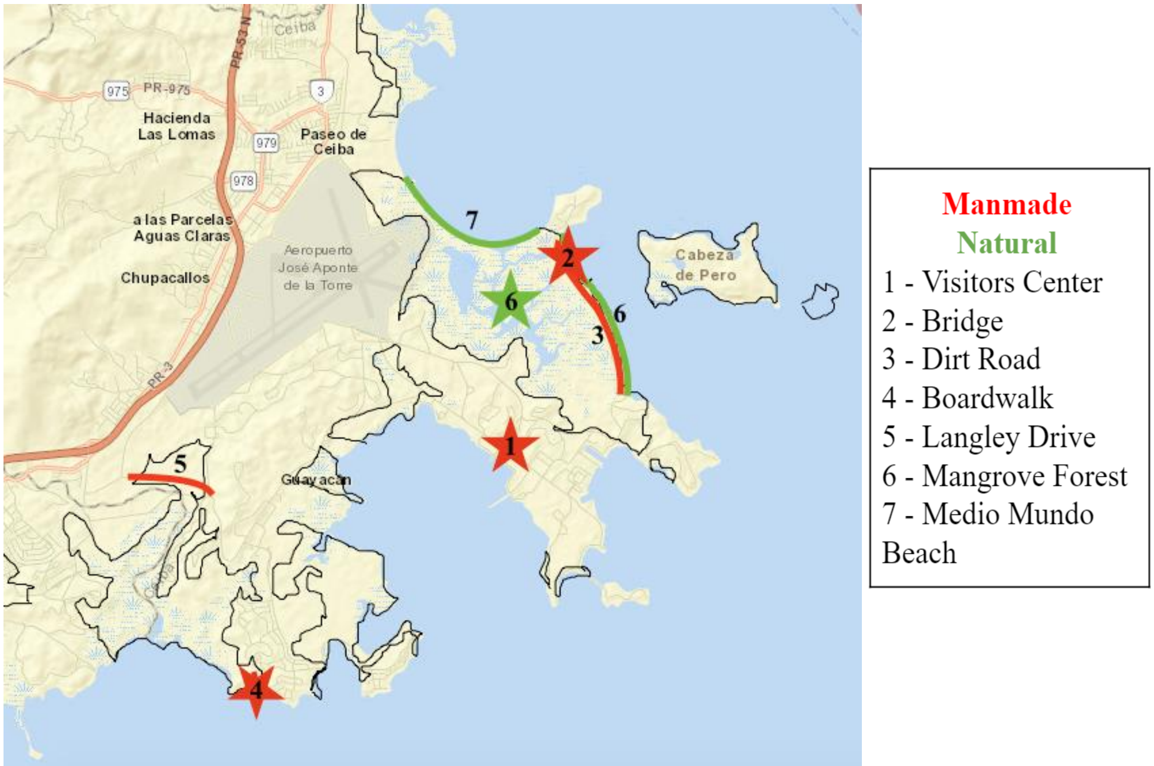


Figure 8. Map showing points of interest in Área Natural Protegida Medio Mundo y Daguao.

4.2 Prioritization of Vulnerable Areas

The areas that were shown to be of interest for proposing adaptation strategies in Las Cabezas de San Juan Nature Reserve and Área Natural Protegida Medio Mundo y Daguao are shown in Tables 6 and 7. Natural systems and infrastructures within each protected area have varying levels of importance and vulnerability. The importance rankings were based on ecological, tourism, cultural, and infrastructural value. To classify vulnerability, we looked at sea level rise, coastal erosion, floodplains, and whether the site was at an elevated risk due to natural disasters. Vulnerability was determined through the identification of regions at risk of ocean inundation from the SLRV and MIPR projections, regions specified by tour guides to be vulnerable to different pressures, and the physical degradation we observed during the site visits. The floodplains were identified using the MIPR data and descriptions were obtained from FEMA (Flood Zones, n.d.). A detailed description of our importance prioritization process can be viewed in Appendix E.1 and detailed description of our vulnerability prioritization process can be viewed in Appendix E.2.

Table 6

Importance and Vulnerability of Las Cabezas de San Juan Nature Reserve

	Importance	**Vulnerability**
Road	• Main access road - leads to El Faro, the boardwalk, Playa Jayuya, Playa Lirios and Playa Canalejo • Used to conduct tours	• Very close to the shoreline • Sections will be inundated after one foot of SLR

	• Barrier between ocean and lagoon	• During extreme weather events, water washes over the road • People trespassing onto the road (destroying the protection between ocean and road) • Covered in sand and fallen trees after hurricanes.
Seven Seas Beach	• Providing protection between the ocean and the road	• Tourists exacerbate erosion • Directly exposed to waves, storms and currents • Already narrow beach, PLN employees stated that the ocean has been advancing inland over time
Playa Jayuya	• Archaeological site with extensive artifacts and human remains found • Provides a buffer zone for coastal ecology and mangroves	• Directly exposed to waves, storms, and currents • PLN Employees stated that there is evidence of coastal erosion • Dunes were 5-10 feet higher 5 years ago
Playa Lirios	• Rocky beach that is part of the tours PLN gives • Evidence of some archeological artifacts	• Less vulnerable than sandy beaches • Directly impacted by storms and sea level rise • Coastal erosion visible
Playa Canalejo	• Archaeological site • Beach provides buffer to erosion and storm damage • Habitat for sandy dwelling species (turtles, birds, etc.)	• Most of the trees along the coast were damaged/killed during the hurricanes, leaving the area very open to erosion • Beach is diminishing due to sea level rise • Sargassum build up
Visitor Center	• Central hub for tourism • Offices for on-site employees • Tree Nursery	• Very close to shoreline • Infrastructure at risk of corrosion and being underwater due to sea level rise

		• Surrounding area will be inundated between one and three feet of SLR
El Faro	• Historical value, it is one of the oldest and best-preserved lighthouses in Puerto Rico • It's a functioning lighthouse • Tourist attraction	• Extreme weather events • Protected from sea level rise by high elevation from the ocean
Laguna Grande	• Rare ecosystem, there are only five similar ones in the world. • Attracts large numbers of tourists every year	• Loss of road may connect ocean to bioluminescent lagoon • Channel gets blocked by sediment, may become worse as sea level rises/ocean currents change • Uncertainty in how sea level rise or an increase in sediment would impact the lagoon
Boardwalk	• The boardwalk serves as a tourist attraction and allows PLN to educate people about the mangroves and nearby Laguna Grande	• As SLR progresses, the foundation of the boardwalk could become unstable.

Table 7
Importance and Vulnerability of Área Natural Protegida Medio Mundo y Daguao

	Importance	**Vulnerability**
Dirt Road	• Main access road to mangrove forest for reserve employees • Facilitates tourism ○ Access for bikes, kayaks, etc.	• More susceptible to erosion than paved roads • Erosion of road visible • High tide within a few feet of the road
Mangrove Forest	• Protects reserve from sea level rise and coastal erosion • Mangroves are efficient carbon sinks	• Very close to shoreline • Hurricane damaged/killed a lot of the mangroves • Uncertainty in the ability to adapt to sea level rise • Sea level rise projections predict this site will be underwater very soon

Bridge	• Access to Pun ta Medio Mundo	• Accelerated corrosion • In danger at high tide • Channel floods up to/over bridge during extreme weather events
Visitor Center	• PLN office • Center for tourism/educational opportunities in the reserve	• No risks identified except for normal risk to extreme weather events.
Medio Mundo Beach	• Tourist attraction • Coastal habitats	• Directly exposed to waves, storms and currents causing coastal erosion • Beach is diminishing due to SLR over time • Sargassum
Langley Drive	• Paved access road, spans large sections of the park	• Proximity to Daguao River and wetlands • Flood risks, especially as extreme weather events become more frequent and severe
Boardwalk	• Provides ability for tourists walk through natural area • Leads to observation tower on coast	• Will be inundated between one and three feet of sea level rise. • Proximity to the coast and relatively fragile wooden construction leads to increased risk from extreme weather events.

Figure 9 is a prioritization matrix that contains all the areas we considered within Las Cabezas de San Juan Nature Reserve during our prioritization process. This offers a useful visualization tool to see how the areas compare to each other. Areas that are in the top right corner are considered the most critical. The raw data that was used to construct this matrix is found in Appendix F.1.

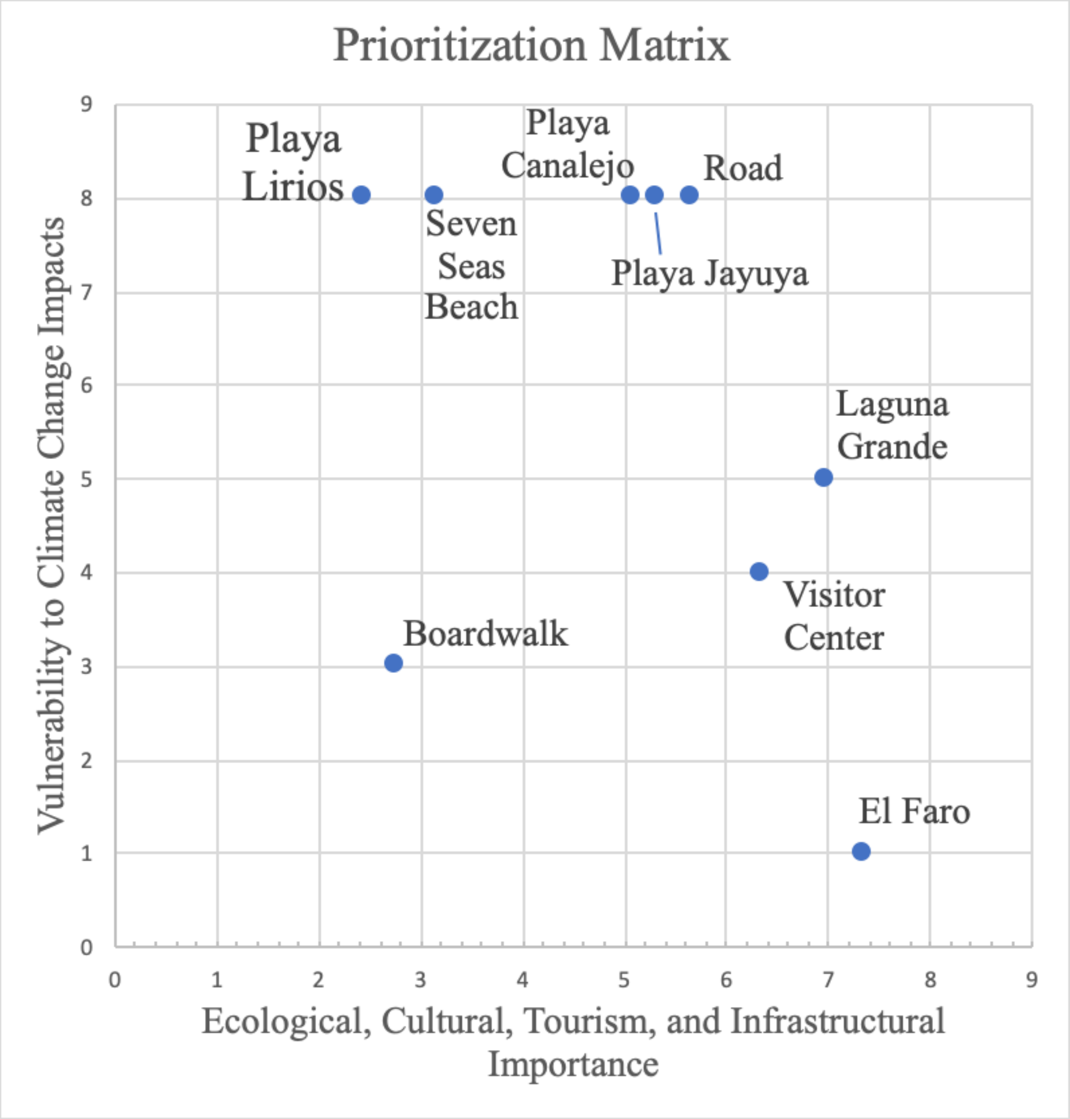


Figure 9. Prioritization matrix of critical areas in Las Cabezas de San Juan Nature Reserve. This is based on ecological, cultural, tourism, and infrastructural importance vs. vulnerability to climate change impacts including SLR, coastal erosion and floodplains.

Figure 10 is a prioritization matrix that contains all the areas we considered within Área Natural Protegida Medio Mundo y Daguao during our prioritization process. This offers a useful visualization tool to see how the areas compare to each other. Areas that are closest to the top right corner are considered the most critical areas. The raw data that was used to construct this matrix is found in Appendix F.2.

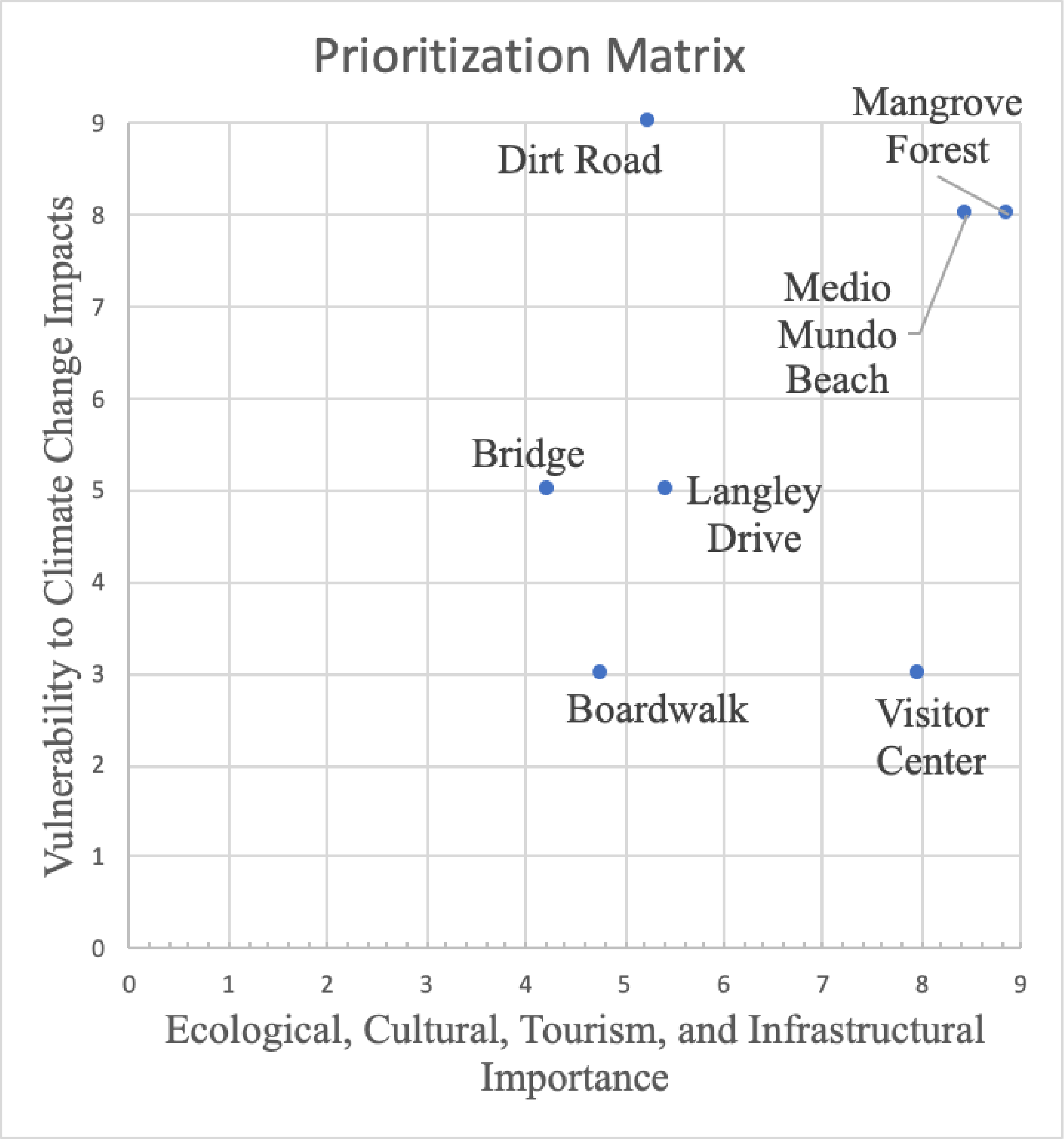


Figure 10. Prioritization matrix of critical areas in Área Natural Protegida Medio Mundo y Daguao. This is based on ecological, cultural, tourism, and infrastructural importance vs. vulnerability to climate change impacts including SLR, coastal erosion, extreme weather events and floodplains.

4.3 Potential Climate Change Adaptation Strategies

According to the PLN employees at Las Cabezas de San Juan Nature Reserve and Área Natural Protegida Medio Mundo y Daguao, it is crucial to protect these areas and maintain their cultural, ecological, infrastructural and tourism value (Personal Communication, 2019). PLN employees Elizabeth Padilla, Antares Ramos Álvarez, Santiago Oliver Báez, and Pablo Ponce De León all emphasized that we should only propose natural methods of adaptation to preserve the aesthetics of the reserve (Personal Communication, 2019). Antares Ramos Álvarez also stated, "I always try to think in terms of human behavior. How can I make it so that I don't need a guard or a policeman watching? (Personal Communications, 2019). An example of this would be providing a few select pathways over a dune to concentrate foot traffic and minimize damage to the rest of the dune. This will allow people to use the area uninterrupted while maintaining the effectiveness of the adaptation strategy.

We found many methods of adaptation that could be utilized to combat climate change. Australia's CoastAdapt system provided adaptation documents separated into four categories: planning, engineering, environmental, social, community, and education (Australian Government Department of the Environment and Energy, 2019). Another useful source for adaptation strategies was the EPA's *Synthesis of Adaptation Options for Coastal Areas*, which included methods specific to coastal regions (U.S. EPA, 2009). Background information provided with the SCAPE Model also contained strategies applicable to archaeological sites (Dawson, 2013). The San Juan Bay Estuary Climate Change Adaptation Plan contained ideas for strategies that might be specifically applicable in the San Juan area (Bauzá-Ortega, 2015). The remaining ideas for adaptation strategies were created with help from Santiago Oliver Báez, Pablo Ponce De León, and Antares Ramos Álvarez, who guided us through the two protected areas and identified regions most susceptible to climate change and suggested potential solutions to the vulnerabilities (Personal Communications, 2019). These strategies are sorted into the table below based on the method, such as replanting or beach development.

Table 8
Climate Change Adaptation Strategies

Adaptation Strategy	Threat(s) Addressed	Potential Locations	Benefits	Constraints
Adaptation Strategies Utilizing Avoidance/Retreat				
Facilitate retreat [2]	Sea Level Rise, Erosion, Flooding	Playa Jayuya, Canalejo, any coastal mangrove areas,	Cost effective, able to maintain ecosystems in their natural state	Not possible where the inland side prevents retreat of natural systems.
Make records before complete loss[3]	Sea Level Rise, Erosion, Flooding	Playa Jayuya, Canalejo	Maintain images and data of historically/culturally significant areas. Typically, more cost effective than protecting the area.	People will no longer be able to view the sites in person.
Adaptation Strategies Utilizing Planning/Development				

Preventive developmental planning [2]	Sea level rise, coastal erosion, increased precipitation	Trail system development los machos, boardwalk, maintenance of lighthouse	Avoid/reduce risk of future damages by locating new infrastructure away from the coast and other potentially hazardous areas.	Limits on areas to develop. Doesn't address current vulnerabilities
Redefine riverine flood hazard zones [2]	Sea level rise, increased precipitation, storm surges	Langley Drive	Protects riverine systems and surrounding zones accordingly	Impacts on flood insurance may require changes to zoning laws which can be difficult
Resilient and adaptive buildings, mainly through elevated structures [1]	Sea level rise, storm surges	Visitor Centers, boardwalks	Manages coastal inundation and flooding that targets infrastructure	Increases developmental costs
Adaptation Strategies Utilizing Planting/Replanting				
Coral replanting [4]	Coastal erosion, sea level rise	Playa Lirios, Seven Seas Beach, Canalejo, Medio Mundo Beach	Wave dissipation and refraction, enhances underwater ecosystem.	Accelerate erosion if done improperly, safety hazard for swimmers, interrupts surf
Replanting trees (sea grape, icaco, maría, almácigo, ucar, emajaguilla, etc.)[4]	Coastal erosion, sea level rise, acts as a carbon sink, storm surges	Dirt Road in Los Machos, Playa Canalejo, Laguna Grande	Could be connected to Project Habitat, provides natural storm break and important habitat. Trees act as a carbon sink.	Takes time for trees to grow
Planting submerged aquatic vegetation (SAV) (e.g. seagrass) [2]	Coastal erosion, sea level rise, reducing impacts of storm surge	Playa Canalejo, Medio Mundo Beach, Playa Jayuya, Seven Seas Beach	Stabilizes sediment, non-invasive, provides aquatic habitat	Grasses diminish in winter months when waves are more severe, sunlight availability is required, may be difficult to plant

Adaptation Strategies Utilizing Natural Materials				
Dune development using sand fencing [5]	Sea level rise, coastal erosion	Seven Seas Beach, Playa Canalejo, Medio Mundo Beach	Naturally made "wall" to protect from ocean damage. Dunes can develop naturally with sand fences	Dunes take time to form, must prevent visitors from destroying dunes
Dune development using sargassum [4]	Sea level rise, coastal erosion	Medio Mundo Beach, Playa Canalejo, Seven Seas Beach	Material already on site. Handles the problem of excessive sargassum on beaches.	Dunes take time to form. Sargassum bales may not be aesthetically pleasing & smell.
Raise ground level using natural materials (i.e. wood chips, sargassum)[5]	Sea level rise, coastal Erosion	Seven Seas Beach	Material available on site. Dead trees need to be disposed of anyways. Handles the problem of excessive sargassum on beaches.	Wood is susceptible to washing away during storms. Sargassum may smell.
Beach nourishment [2]	Flooding, erosion, sea level rise	Seven Seas Beach, Playa Canalejo, Medio Mundo Beach, Playa Lirios	Flexible and fast coastal management option. Complement other adaptation strategies. Provides flood and erosion protection.	Can affect shoreline ecosystems (i.e. burying sea turtle eggs). Usually an ongoing process. Need to have a good source for sand
Resurface roads [5]	Erosion from sea level rise	Dirt road in Los Machos	Provides more structure for the road to reduce erosion	Requires a lot of manpower and time to implement
Construct levees to reduce flooding along estuaries and coastal streams [1]	Sea level rise, increased precipitation, flooding	Langley drive, dirt road in Los Machos	Reduces/controls flooding	Transfer of risk elsewhere, could cause erosion problems, disconnects estuary and wetlands

Note: Strategies adapted and compiled from the following sources: (Australian Government Department of the Environment and Energy, 2019)[1], (U.S. EPA, 2009)[2], (Dawson, 2013)[3], (Bauzá-Ortega, 2015)[4], Interviews with Santiago Oliver Báez, Pablo Ponce De León, and Antares Ramos Álvarez (Personal Communications, 2019)[5]

4.3.1 Application and Economic Analysis of Adaptation Strategies

The following costs associated with executing climate change adaptation strategies are estimates and may vary based on where they are implemented. This information can be used as a guide for future application.

Coral Replanting

- **Simple transplantation costs** are estimated at $1 per square meter for Elkhorn Coral. These costs include the collection, transportation and placement by trained locals. Monitoring costs are excluded from this estimate (Spurgeon, 2001).

Planting Mangroves

- Ahmed Pérez provided **planting guidelines** for mangroves in coastal areas. Mangroves should ideally be grown in a nursery to a height of three to four feet. The mangroves should then be planted at a spacing of five feet in staggered rows (Personal Communications, 2019).
- Generally, when considering the **width of the mangrove belt**, larger is better. 100 meters of mangrove can reduce wave height by up to 66% which will help to protect against erosion further inland. A denser mangrove forest is more effective than a sparsely populated one (Spalding, McIvor, Tonneijck, Tol, and Van Eijk, 2014).
- According to Ahmed Pérez the **cost of planting** and maintaining a tree for five years is $60 (Personal Communications, 2019). It would cost $540 to cover an area of 10 feet by 10 feet.
- The **coastal mangrove belt in Los Machos** is approximately 6,400 feet long. Red mangroves are best suited to this location because of the salinity conditions and the wave action of the coast. There are still some living mangroves closer to the inland road that would not need to be touched. Assuming a belt width of about 15 feet that needs to be restored, it would cost approximately $8,000 for every 100 feet of length, or $518,000 to restore the entire coastal mangrove belt at this location to its previous condition.
- Alternatively, it would be significantly cheaper to plant the seeds. However, the survival rate is much diminished and the time period to maturity is at least 5 years longer resulting in a longer period of vulnerable coastline.

Planting Uva de playa (Sea Grape)

- Proper **plant spacing** will ensure the Sea Grape plants are as effective as possible at preventing erosion. The plants are salt resistant and have an extensive root system that makes them well suited for this purpose. The plants should be located in rows about three feet from each other with about 3 feet between rows to allow for maximum growth and coverage. If multiple rows are planted, the rows should also be staggered (South Florida Plant Guide, n.d.). Planting more rows will provide more protection but will minimize the amount of available beach area.

- According to Ahmed Pérez the **cost of planting** and maintaining a tree for five years is $60 (Personal Communications, 2019). To plant one row of Sea Grape Trees 100 feet long would cost approximately $2,000.

Planting Beach Grass

- American beach grass is sold in 100-stem bundles for approximately $35 to $55 per bundle. It is recommended that grasses are planted with a spacing of two or three stems to a hole at 1- to 3-foot intervals, resulting in a **cost of under $0.50 per square foot** of dune. (Eastern Research Group, 2013).

Planting Sea/Eel Grass

- Estimated cost according to a University of Cambridge study is **$45,000 per acre** only considering the costs of collection, preparation & installation of planting units. Cost are much higher if permitting and monitoring costs are included (Estimated cost of seagrass restoration, 2001). Sea grasses are typically planted at depths of one to nine meters depending on the species.
- Another study recommends that planting by **seed rather than transplanting** provides a more cost-effective approach to planting sea grass while minimizing ecological impacts on donor beds (Restoration of Seagrass Meadows, n.d.). However, this study did not include specific cost information.

Dune Development

- **The cost of sand fencing** is $59.95 for a roll that is 50 feet long and four feet tall. At Playa Canalejo, which is about 3,250 feet long, enough sand fencing could be purchased to be installed on the entire length of the beach for only $3,900 (Natural wood snow/sand fence, n.d.). This value does not include labor costs. A similar effect can be achieved using wooden pallets, which are often available in large quantities at locations with shipping/receiving facilities and could potentially be acquired for low/no cost.
- **The cost of sargassum bales** would be solely based on purchasing a seaweed baler and baling twine which would cost approximately $3,800 (Alibaba, n.d.). There is a surplus of sargassum on the beaches that could be used to support this strategy.

Raise Ground Level Using Natural Materials

- Raising the ground level using natural materials such as sargassum or wood chips is a cost-effective strategy because the materials are already present in large quantities on site. The only potential costs associated with this activity would be labor, but even this would likely be low as the desired effect could be completed with relatively low effort.

Constructing Stone Levee

- **The cost of materials f**or the installation of stone levees is dependent on the depth of the levee (FEMA, 2007).
    - Two feet deep would cost $60 per linear foot.
    - Four feet deep would cost $106 per linear foot.
    - Six feet deep would cost $170 per linear foot.
- This strategy would require maintenance to avoid blockage and destruction to the levee, which may result in an additional cost (Eastern Research Group, 2013).

Reinforce Dirt Road in Los Machos

- While there are many different types and **sizes of stone** available, any standard crushed stone with a top size around three inches (measuring at least three inches in one dimension) is likely best suited for this application. Stone of this size will be resistant to being washed off the road surface, promote drainage, stabilize sediment, and provide a suitable driving surface for the vehicle traffic this road experiences. Stone should be laid down at a minimum **thickness** of four inches as it will compress naturally over time.
- Crushed stone with a three-inch top size is estimated to cost between $15 and $25 per ton installed. Because Puerto Rico is and island and procuring materials may be more difficult, using $25 per ton will provide a more conservative estimate. One ton translates to roughly 0.74 cubic yards of stone, and to cover a 10-foot-long section of road with four inches of stone, it would take 1.23 cubic yards. This translates to a cost of $**42 for each 10-foot-long section of road** covered. (Dirt, gravel, and low volume road program: Typical costs, 2015)

Beach Nourishment

- **The cost of beach nourishment** is between $300 to $1000 per linear foot, which accounts for material, transportation, and labor (Eastern Research Group, 2013).
- Seven Seas Beach is approximately 3,500 linear feet long, resulting in a cost of $1,050,000 to $3,500,000 to replenish the entire beach.
- Best practice for beach nourishment is to use material, in this case sand, that is similar to the existing beach material. It is not required to nourish the entire length of the beach and would be more effective to target areas most impacted by sea level rise and coastal erosion.

Waterproofing Infrastructure

- For infrastructure, roof sealant will provide a waterproof barrier to protect against increased precipitation and extreme weather events (Cost Owl, 2019). The sealant is a coating applied like paint and is durable enough to withstand heavy rainfall.
- **The cost of roof sealant** can range from $15 to $30 per gallon, where one gallon will typically cover an area of 100 square foot to 150 square foot (Cost Owl, 2019).
- On average, **labor costs for roof sealant** are $0.50 per square foot (Cost Owl, 2019). However, volunteers or employees within the organization may be utilized to complete this task.
- For example, a 200 square foot roof would cost between $30 and $60 for materials and $100 for labor for a **total cost** of $230 to $260.

Raising Infrastructure

- **The cost of raising infrastructure** would range from $60 to $90 per square foot for a full service. This would include all elements of structural, architectural, and engineering design and construction (Dawson Foundation Repair, n.d.).

- The main structure of the **visitor center at Las Cabezas** de San Juan Nature Area measures 40 feet by 40 feet, which would translate to a total estimated cost of $96,000 - $144,000 to farther elevate the structure.

5.0 Conclusions and Recommendations

This section presents our conclusions and recommendations based on our findings in the previous section. This will provide PLN with adaptation strategies to protect specific areas within their reserves that are being impacted by climate change. These recommendations have the potential to be extended into other regions, as climate change is a global issue that impacts infrastructure and surrounding environments. With careful implementation, adaptation strategies have the potential to extend the useful life of infrastructure and protect sensitive ecosystems. Our findings support this claim; we have found that it is crucial to address critical areas within these sites to reduce the risk of complete loss or to extend the time before complete loss occurs. A system of monitoring the sites and the use of volunteers will be important to the success of the adaptation methods. However, there are constraints when working with these regions. Adaptation strategies may not be feasible for certain locations in the reserve. Furthermore, to preserve the aesthetics of each protected area, hard adaptation strategies typically will not suffice. Finally, the site itself may also pose challenges to adaptation efforts.

The assessment phase in our methodology revealed that both Las Cabezas de San Juan Natural Reserve and Área Natural Protegida Medio Mundo y Daguao need innovative adaptation strategies to combat the effects of climate change. From our findings, we can conclude that the reserves will be, or are currently being impacted by, SLR, coastal erosion, storm surges, increased precipitation, an increase in frequency and severity of natural disasters, ocean acidification, and flooding. Because climate change is a global issue, we can also conclude that similar coastal areas in other regions will be impacted by these effects. Through content analysis of PLN management plans and observations made while on site visits, we determined that both sites feature areas that are important based on environmental, tourism, cultural and infrastructural factors. Using this information and the vulnerability of specific sites to climate change impacts, we completed our prioritization objective. Critical areas within each site were identified as those that have either the most relative value, are in the most danger from climate change impacts, or both. This reported that the access road and Playa Jayuya within Las Cabezas de San Juan Nature Reserve and the coastal mangroves and dirt access road within Área Natural Protegida Medio Mundo y Daguao should be prioritized based on their importance and vulnerability.

Utilization of volunteers and implementation of a monitoring system are important to the success of the adaptation methods. PLN works with two types of volunteers: occasional volunteers and recurring volunteers (Para la Naturaleza, Who Are We?, n.d.). Most, if not all, of the labor involved in implementing the adaptation strategies could be completed by volunteer groups under the supervision and guidance of knowledgeable experts. This would eliminate or reduce the labor costs, leaving more funds for other aspects. These groups will be helpful for strategies that require a lot of manpower, like planting trees. Once these methods are put into place, a method for monitoring is required for maintenance and determining whether the strategies are adequate (Fideicomiso de Conservación de Puerto Rico, 2010.a). Creating a Management Advisory Board to oversee the original implementation and maintenance of the regions would improve the preservation of the site. (Fideicomiso de Conservación de Puerto Rico, 2010.a). This could also consist of volunteers that collect data and observations at each of the sites, such as measuring and reporting rates of sea level rise or coastal erosion.

Most traditional strategies, particularly hard adaptation strategies, cannot be used in these protected areas. Because of high tourism rates, it was necessary to consider alternative strategies, or combinations of several existing techniques to meet the needs of each area. It is essential to evaluate the aesthetic impacts of any strategies that are selected to preserve the natural appearance. Strategies that are implemented in protected areas need to be as natural as possible, and minimally invasive. This was reiterated when Antares Ramos Álvarez, Santiago Oliver Báez, Pablo Ponce De León, and Elizabeth Padilla insisted that invasive methods, such as building concrete walls, would greatly diminish the natural value of the site (Personal Communication, 2019). Because of this, we will not be recommending intrusive methods.

Certain characteristics of areas within the protected areas could make implementing the most appropriate adaptation strategy difficult or impossible. There are areas within the reserves that are remote and have limited access. Playa Jayuya, a sandy beach in Las Cabezas de San Juan Nature Reserve, can only be reached by walking on foot for approximately 30 minutes or by boat. Boat access is made difficult when considering the fragile coral reefs present offshore. Getting resources into this area and others like it would be an intensive process. In protected areas like these impacted by climate change, it is important to protect the existing conditions while still implementing effective adaptation strategies. Some aspects of certain areas eliminate strategies that would otherwise be considered the best option. For example, on sandy beaches, Antares stated that beach nourishment could be a potentially helpful option to help adapt to sea level rise and coastal erosion. However, Playa Jayuya contains archaeological artifacts that are in the process of being uncovered. As Antares Ramos Álvarez explained, dumping large amounts of sand onto this beach would be counterproductive towards these efforts (Personal Communication, 2019). This points to a larger problem with existing management plans that propose adaptation strategies without considering the site-specific conditions.

PLN recognizes the potential for partial or complete loss of their sites due to SLR and natural disasters, despite the efforts made. Elizabeth Padilla stated that within 100 years, they expect the reserve at Las Cabezas de San Juan to be a series of islands because of SLR (Personal Communication, 2019). The data from the MIPR supported this conclusion. In some cases, the best option may be to do nothing and focus efforts elsewhere. There may be cases where the effects of climate change are going to impact an area so aggressively that no amount of resources are able to save it. SLR is impacting the entire world. Areas throughout the Caribbean and other tropical regions should be particularly aware of these potential losses since the effect of steric SLR accelerates the rate that the ocean rises in warm regions.

It is difficult to define how quickly SLR is progressing and when impacts will begin. Organizations around the world have attempted to quantify SLR and make projections for the future. This typically comes in the form of the sea level increase from current levels by the year 2100. The high end of these projections predict a 5.9 foot SLR by the year 2100. (Ezcurra & Rivera, 2018). Low ends of similar projections indicate increases in sea level of only 0.85 feet are to be expected by 2100. (IPCC, 2018). These discrepancies arise from unknown rates of future carbon dioxide emissions and glacial ice melt (NOAA Office for Coastal Management, n.d.). In addition, the effect of steric sea level rise, caused by an increase in water temperature, affects hot tropical zones more than temperate zones. This can lead to local variance and a faster rate of SLR in regions like Puerto Rico (Bauzá-Ortega, 2015). While there is no widespread agreement on the rate of SLR, most organizations agree on the fact that it is accelerating. PLN’s management plan pointed towards a SLR rate of 0.07 inches per year from 1961 to 2003, and an increase of 0.12 inches per year when only considering the 10 year period from 1993 to 2003. Another study has predicted that total SLR in the 21st century will be four times as much as in the 20th century (Camber, n.d.) Rates of SLR have been measured as high as 0.53 inches per year locally in Puerto Rico in recent years. (Bauzá-Ortega, 2015).

5.1 Recommendations

This section includes recommendations for a range of general areas found within our sites. The timeframe of this project did not allow us to consider every area within the two sites. These general recommendations have been included not only for the areas we did not get to consider within our sites, but also for future projects. PLN manages many other sites around the island that will need climate change adaptation strategies in the future. In addition, climate change is a problem on a global scale. While the specific characteristics of each site always need to be considered, these general recommendations will be able to serve as a basis for groups everywhere to begin implementing adaptation strategies. We hope that these recommendations can be utilized by other stakeholders who are involved in the management of protected areas, since our research revealed that there was not a comprehensive list of non-invasive adaptation strategies already developed. We have also included strategies for the specific areas that we selected in Las Cabezas de San Juan Nature Reserve and Área Natural Protegida Medio Mundo y Daguao.

5.1.1 General Strategies for Adaptation

Roads

- Our assessment suggests that roads in coastal areas can be at risk from erosion, SLR, and flooding. Information that we gathered from the CoastAdapt guidelines contained several strategies concerning infrastructure such as roads (Australian Government Department of the Environment and Energy, 2019). In the short term, maintaining buffer zones on the sides of roads can protect from erosion and inundation. This can include restricting tree harvest from borders and planting coastal grasses, mangroves, and other trees to provide natural protection from water and storm damage. The most effective trees will vary based on the region of implementation. It is important to consider that trees with large surface roots close to a paved surface could damage the road, as well.
- Also, in areas that river flooding is likely to impact roads according to FEMA and GIS maps, fortify edges of road through stone placement to reduce undercutting and surface erosion. This can also include the installation of stone levees to help divert water from the road.
- For a long-term solution, bridges with stable foundations could be built to raise the level of the road, accommodating rising water level. However, this may come at an extensive cost and, therefore, should be considered as a project in the future. In underdeveloped regions, this cost may not be feasible to ever implement.
- Unfortunately, it may be necessary to accept that some roads may be lost and maintaining access will be more effective through other means, such as boats or bridges.

Boardwalk

- As the sea level rises, the foundations and walking surfaces of boardwalks can be compromised. For protection of a boardwalk, raising the level of the boardwalk should be incorporated into the regular repair and maintenance plans. Information gathered during interviews indicated that most boardwalks already undergo periodic maintenance, so this strategy will be easy to incorporate and will serve as a gradual, noninvasive method. There is no large risk, except in regions where waves and erosion are much more likely.
- When choosing new places to build boardwalks, choose areas that will be less susceptible to flooding and SLR when possible.

- In peak interest areas, accept that regular maintenance and replacement may be needed to maintain tourist access.

Archaeological Sites

- A study of vulnerable coastal archaeological sites in Scotland featured several strategies for the protection of these areas (Dawson, 2013). Focusing excavation efforts to the regions most susceptible to climate change impacts will minimize the loss of archaeological artifacts.
- Utilization of volunteers could aid in this process.
- Dune enhancement, supplemented with stones between water and excavation, can provide more time for extraction.
- Ocean inundation is inevitable, and a potential solution could include underwater excavation.

Mangroves

- Many of the areas that we have studied are in danger due to SLR and extreme weather events. We recommend beginning planting more at slightly higher elevations to facilitate migration. When planting new mangroves, ensure that the average salinity of the area is suited for the specific species being planted as each type is specially adapted to specific regions. Red mangroves will be the most valuable for coastal protection and SLR, as stated by Santiago Oliver Báez and Pablo Ponce De León (Personal Communication, 2019).
- Also, dead mangroves should be removed in stages, while planting in coastal areas that were damaged by hurricanes and storm surges. From our site visits, there areas with noticeable damages to mangroves from Hurricanes Irma and Maria. Other coastal mangroves in the area have likely suffered similar damages. It will be more effective to remove strips of dead trees further inland and closer to roads first, as the dead trees closer to open water will provide temporary protection from harsh weather while growing. When removing dead trees, the lowest portion of the trunk and roots can be left to provide more sediment stabilization features for the area. The dead trees that are removed can also be woven into the roots of the outermost dead as a natural and permeable protection to storm surges. The belt of replanting can progressively be moved outward as time and resources are available.
- From our interview with Pablo Ponce De León, we determined that a buildup of sediment in canals can restrict water flow to mangrove forests (Personal Communications, 2019). Canals that lead to mangroves should be dredged so that new water regularly enters mangrove forests. This can help maintain their health and ensure they do not develop excessively high levels of salinity, which reduces mangrove populations in certain area. With increased frequency of drought in some regions, these sealed mangrove areas can increase to levels that will kill the mangroves, reducing habitat and making surrounding mangroves more vulnerable to rising water levels. Dredging channels will become less important as water level rise will naturally provide influx of water.

Sandy Beaches

- Based on our finding that invasive methods will not suffice in natural areas due to their unattractiveness, we recommend that hard structures, such as dikes and seawalls, are not installed. This is because they will cause more damage and costs then they will be worth.

Furthermore, they will destroy coastal habitat and will interfere with natural appearance of coastal zones, potentially impacting tourism and therefore influx of revenue.

- Less invasive alternatives include replanting sea grasses or restoring and planting Staghorn and Elkhorn coral in coastal reefs to strengthen natural breakwater of the reefs. As water level rises, plant at a higher elevation. When considering coral restoration, using micro-fragmentation would be useful to decrease the amount of time to maturity of the coral from 25 years to 3 years (Page, 2018). This method was utilized in the Florida Keys, where it proved successful in improving the rate of growth. Enforcing types of fishing restrictions near coral can prevent more damage to the ecosystem and natural break waters that the coral provides.
- We found that facilitating dune growth can protect the beach itself, as well as adjacent infrastructure or ecosystems, such as roads and mangrove forest (Personal Communication, 2019; U.S. EPA, 2009). From this we determined that replenishment should increase accretion and reduce sand loss due to erosion through the use of sand fencing, beach nourishment in some areas, and collecting and baling sargassum to both reduce its negative impacts on coastal ecology and to naturally facilitate dune growth.
- Unless a beach is protecting valuable infrastructure, change and migration inland of the coastline is a natural process that should be allowed. This is known as facilitating retreat as has been used successfully in Buzzards Bay, Massachusetts (U.S. EPA, 2009).

Rocky Beaches

- Planting trees and plants in coastline can help reduce erosion. If the conditions are suitable, we suggest planting mangroves slightly out in the water to lessen energy of waves when it reaches. Unless the site is heavily visited or adjoining a road or other infrastructure, PLN should allow erosion and natural progression inland of coastline and to relocate coastal plants farther inland to maintain the migrating habitat. This strategy of facilitating retreat has been recommended for natural coastal areas by the EPA (U.S. EPA, 2009). Planting coral offshore can provide a natural breakwater effect and dissipate wave energy to protect land from coastal erosion. When considering coral restoration, using micro-fragmentation would be useful to decrease the amount of time to maturity of the coral from 25 years to 3 years (Page, 2018). This method was utilized in the Florida Keys, where it proved successful in improving the rate of growth. Enforcing types of fishing restrictions near coral can prevent more damage to the ecosystem and natural break waters that the coral provides.

Built Infrastructure

- Before building new structures, we recommend preventive planning by considering GIS SLR projections and other climate risks. When possible, build in areas which are less likely to be impacted by flooding and SLR (U.S. EPA, 2009).
- Adapt infrastructure by raising existing structures in at risk areas on stilts to protect from the effects of flood damage as recommended by Australia's CoastAdapt documents (Australian Government Department of the Environment and Energy, 2019). Ensure existing structures are regularly inspected and maintained. Corrosion caused by changes in humidity can weaken structures and should be identified.
- Also, fortifying roofs to effectively shed water will reduce impacts of extreme weather events. This can include waterproofing sealant.

5.1.2 Site Specific Recommendations

For all of the following specific recommendations it should be noted that all of the recommended strategies we present can extend the life of current infrastructure, but do not provide a permanent solution to the impacts of climate change. More drastic adaptations to the changes for infrastructure will eventually be needed to maintain operation and access to the reserves. Climate change will impact areas and adaptation strategies in unexpected and different ways in each site of implementation. Monitoring the results of adaptation is important to evaluate if the success of the chosen strategies and determine if alternative strategies should be used. Furthermore, natural systems are typically able to adapt on their own in some areas letting nature adapt and change rather than trying to maintain the current ecosystem will be beneficial.

For Las Cabezas de San Juan Natural Reserve:

Access Road

- The GIS data from the MIPR suggests that sections of the road will be inundated after one foot of SLR (Government of Puerto Rico, 2015). To protect the road for as long as possible, we recommend raising the ground level in the belt of trees using natural materials, preferably ones located on site. Using natural materials will minimize the environmental impact and preserve the natural appearance of the area. This idea was developed after speaking with Regional Superintendent Antares Ramos Álvarez during our site visit (Personal Communications, 2019). Wood chips are recommended because there are a lot of trees on site that were killed during the hurricanes and need to be disposed of and PLN has a large chipper. Sargassum would also be a good option because it is already located on site in large amounts, and this would help with the excessive build up on the beaches during certain times of year. Sargassum does have a propensity to smell while decomposing which could be either a benefit or shortcoming. It would be a benefit because it would subtly dissuade beach goers to walk through the tree belt onto the access road, however it could also un-appealing for tourists visiting the reserve. If this area is being built up, it is important to provide access through/over this area for tourists that will inevitably be traveling from the beach to the road. Additionally, while spreading material to build up the ground level it is important to spread one thin layer at a time so that the implementation is subtle and does not negatively impact the plant life in that area.
- These strategies, combined with those specified below for Seven Seas Beach, have the potential to extend the useful life of this road. However, it is realistic to prepare for the loss of this road since sections will be inundated after as little as one foot of SLR (Government of Puerto Rico, 2015).

Seven Seas Beach

- From our GIS images and site visits, it was apparent that the beach would be affected by SLR and erosion. Planting Uva de playa in staggered rows at the top of the beach spaced three feet apart to stabilize sediment and provide a windbreak effect. This information was given to us by Ahmed Pérez. He stated that these trees would be useful in protecting the coast because they are suited to high salt conditions (Personal Communication, 2019).
- Another potential strategy is beach nourishment with sand to combat the effects of sea level rise and coastal erosion. This strategy has been used in other projects around the US as stated in the EPA *Synthesis of adaptation options for coastal areas* (2009). Beach nourishment requires continued maintenance as the newly added sand will be eroded away

over time. Therefore, it should be used sparingly in areas where the beach is eroding at a particularly fast rate (U.S. EPA, 2009).

- Planting coastal grasses to stabilize sediment is another solution that could improve the quality of the beach. Planting aquatic grasses can minimize wave energy at the beach, while also stabilizing sediment. Different areas such as the Chesapeake and Tampa Bays have utilized these strategies to protect the coast. (U.S. EPA, 2009).
- In addition, restoration of offshore reefs can act as a natural breakwater and diminish wave energy; it also serves as a habitat for aquatic life. Potential coral species include Elkhorn and Staghorn coral because they grow quickly to a large size and exhibit resilience. Coral should only be planted at locations of existing reefs, or else there is a risk of disrupting currents and causing unintended erosion elsewhere. We developed this recommendation by examining previous uses of coral restoration in the San Juan Bay Estuary Climate Change Adaptation Plan and speaking with Regional Superintendent Antares Ramos Álvarez. (Bauzá-Ortega, 2015; Personal Communications, 2019)

Playa Jayuya

- This site has restricted access which would make the implementation of adaptation strategies difficult. Pablo Ponce de León explained that the site can only be accessed via a 30-minute walk on foot, or potentially by boat if the offshore coral reefs can be navigated (Personal Communication, 2019). For a site like this, we recommend that PLN concentrates excavation efforts to remove archaeological artifacts before ocean inundation occurs. From the MIPR data, this site is expected to be inundated after three feet of sea level rise (Government of Puerto Rico, 2015). With limited time and effects of sea level rise already present, this excavation is high priority.

Playa Lirios

- Because this is a rocky beach, it is naturally more resistant to erosion than the sandy beaches we considered. However, the rocky ground also means that strategies such as beach nourishment, tree planting, and dune development are not applicable here. By examining previous uses of coral restoration in the San Juan Bay Estuary Climate Change Adaptation Plan and speaking with Regional Superintendent Antares Ramos Álvarez, we were able to develop this recommendation (Bauzá-Ortega, 2015; Personal Communications, 2019). In this location, we recommend restoring offshore coral reefs to act as a natural breakwater can help prevent further coastal erosion. Potential coral species include Elkhorn and Staghorn coral because they grow quickly to a large size and exhibit resilience. Coral should only be planted at locations of existing reefs, or else there is a risk of disrupting currents and causing unintended erosion elsewhere.
- Assisting the migration of coastal plants by planting further inland where shoreline will be receding to. This can help reduce the impact of erosion on the coast. The practice of allowing coastal ecosystems to move inland is known as facilitating retreat, and the EPA has cited successful uses of this strategy in Buzzards Bay, Massachusetts (U.S. EPA, 2009).

Playa Canalejo

- At Playa Canalejo, the restoration of offshore coral reefs can act as a natural breakwater and diminish wave energy; it also serves as a habitat for aquatic life. Potential coral species include Elkhorn and Staghorn coral because they grow quickly to a large size and exhibit resilience. Coral should only be planted at locations of existing reefs, or else there is a risk of disrupting currents and causing unintended erosion elsewhere. We developed this recommendation by examining previous uses of coral restoration in the San Juan Bay Estuary Climate Change Adaptation Plan and speaking with Regional Superintendent Antares Ramos Álvarez. (Bauzá-Ortega, 2015; Personal Communications, 2019)

- Antares Ramos Álvarez requested that a strategy be developed to reinforce the dunes along the beaches (Personal Communication, 2019). She supplied us with preliminary ideas that we supported with information from The Commonwealth of Massachusetts Sand Fencing Report (2018). Dune development can be accomplished by two methods in this location. Sand fences, in the form of wooden pallets or wire-strung wooden planks, are placed towards the top of the beach and will naturally develop a dune over time by slowing down the wind to catch airborne sand particles. The sand fences are most effective when spaced with 50% slats and 50% open space. The posts should be spaced approximately 4 feet apart and inserted at least 4 feet into the ground for optimum effectiveness (The Commonwealth of Massachusetts, 2018). A similar effect can be accomplished by using sargassum bales. Because the sargassum is already present on Playa Canalejo in excessive amounts, this would be an efficient use of resources. The sargassum should be baled into bales measuring about 2.5 feet by 2.5 feet by 2 feet for transport. These bales should then be placed on the windward side of the dune (Bauzá-Ortega, 2015).
- Planting Uva de playa in staggered rows at the top of the beach spaced 3 feet apart to stabilize sediment and provide a windbreak effect. This information was given to us by Ahmed Pérez. He stated that these trees would be useful in protecting the coast because they are suited to high salt conditions (Personal Communication, 2019).
- Planting aquatic vegetation is another useful strategy. Planting aquatic grasses such as eelgrass can minimize wave energy at the beach, while also stabilizing sediment. Different areas such as the Chesapeake and Tampa Bays have utilized these strategies to protect the coast. (U.S. EPA, 2009).

Visitor Center

- The GIS data from the MIPR indicates that the visitor center is not in immediate danger as it will not be inundated until sea levels rise six feet. However, the area will be at risk of erosion and flooding during extreme weather events at lower levels of sea level rise. Because the building is already raised approximately three feet above ground level it is already partially protected against these effects. As the sea level continues to rise, flooding may become more frequent and the elevated water level will provide a higher base for storm surges. If future conditions indicate that the current elevation of the building is not sufficient, then it may be necessary to elevate the structure farther to remove it from at risk zones. This adaptation has been recommended in similar situations by Australia's CoastAdapt system (Australian Government Department of the Environment and Energy, 2019).

El Faro

- According to our research, El Faro is only slightly as risk to the impacts of climate change, specifically extreme weather events and natural disasters. The lighthouses high elevation protects it from SLR and coastal erosion. Based on statements from PLN Environmental Interpreter Pablo Ponce De León indicating that El Faro had previously been damaged during hurricanes, we recommend that they prepare for increased frequency and intensity of extreme weather events (Personal Communications, 2019). This can be achieved by ensuring that the structure is completely waterproof and able to withstand winds and rains that may exceed historic records.

Laguna Grande

- Currently, we do not recommend any adaptation strategies for the Laguna Grande. The only potential threat that has been identified to the area is a larger than normal influx of ocean water, but historically the bioluminescent organisms have been resilient and able to adapt. At this point, no one that we talked to had any knowledge on the impacts on the bioluminescent lagoon due to climate change (Personal Communication, 2019).

Boardwalk

- During future renovations, we recommend raising the boardwalk as necessary to accommodate SLR and protect from flooding. From our assessment portion of our methodology, the boardwalk will be impacted by SLR at six feet. This future planning of this piece of infrastructure will help with its adaptation to climate change (Government of Puerto Rico, 2015).

For Área Natural Protegida Medio Mundo y Daguao:

Future Trails

- Facilities Manager Santiago Oliver Báez expressed the hope of developing walking trails within the park and specifically the edge of Los Machos to make it more accessible to tourists. These should be located outside of zones at risk of sea level rise for simpler management. To make the mangroves accessible to tourists, building boardwalks higher in at risk areas will accommodate some changes in sea level.

Dirt Road

- We recommend restoring the coastal mangrove belt to its former condition, and potentially extending it further into the ocean. This will help to protect the road from waves, slow SLR, and stabilize erosion in the area. This is discussed in more detail in the coastal mangrove section below.
- At sections of the road where erosion is already present, we suggest reinforcing the road with crushed stone. This natural material will promote drainage and slow erosion of the roadway. This strategy was developed by speaking with Facilities Coordinator, Santiago Oliver Báez (Personal Communications, 2019).

Coastal Mangroves

- From our assessment, we find that the mangrove forest will be impacted by one foot of SLR and any extreme weather events (Government of Puerto Rico, 2015). We recommend that efforts should be made to remove dead mangroves and other vegetation to make space for planting new mangroves. As time and manpower is available, we recommend planting the mangroves in bands. Cutting belts closest to the road and replanting those first so that the outer dead mangroves will provide protection for the young trees as they begin to grow. The replanting of new mangroves trees would help protect the coast, rising the surface level of the ground, and is more attractive for tourists exploring the reserve (Bauzá-Ortega, 2015).

Bridge

- Santiago Oliver Báez was concerned with the condition of the bridge, as its integrity is jeopardized during high tide and extreme weather events (Personal Communication, 2019). This makes the bridge susceptible to accelerated corrosion due to ocean acidification and flooding. This means it will likely require more frequent replacement than necessary in the past. This is crucial to maintaining the structural integrity and safety of the bridge, as corroded metal could cause the system to fail. When the channel floods, the water flowing through can exert a great deal of force on the bridge that could potentially damage the structure. During future construction of a new bridge, we suggest raising the level of the bridge to accommodate the rising sea level as this area is expected to be inundated after six feet of SLR (Government of Puerto Rico, 2015). Elevating the bridge so that it is no longer underwater during flood events would likely extend its useful life.

Visitor Center

- The visitor center is not directly threatened by the effects of climate change, unless there are unpredicted impacts on the nearby shore. The GIS data from the MIPR indicated that this structure would not be threatened, even with six feet of SLR (Government of Puerto Rico, 2015). At this time, we do not recommend any actions at the visitor center.

Medio Mundo Beach

- Antares Ramos Álvarez requested that a strategy be developed to reinforce the dunes along the beaches (Personal Communication, 2019). She supplied us with preliminary ideas that we supported with information from The Commonwealth of Massachusetts Sand Fencing Report (2018). The development of dunes or the enhancement of existing ones will provide a barrier at the top of the beach. Dune development can be accomplished by two methods in this location. Sand fences, in the form of wooden pallets or wire-strung wooden planks, are placed towards the top of the beach and will naturally develop a dune over time by slowing down the wind to catch airborne sand particles. The sand fences are most effective when spaced with 50% slats and 50% open space. The posts should be spaced approximately 4 feet apart and inserted at least 4 feet into the ground for optimum effectiveness (The Commonwealth of Massachusetts, 2018). A similar effect can be accomplished by using sargassum bales. Because the sargassum is already present here in excessive amounts, this would be an efficient use of resources. The sargassum should be baled into 2.5 feet by 2.5 feet by 2 feet for transport. These bales should then be placed on the windward side of the dune (Bauzá-Ortega, 2015). Wherever dunes are built up, it is important to provide access through them for people at a few select locations so that the dunes are not worn down by foot traffic.
- Planting Uva de playa in staggered rows at the top of the beach spaced 3 feet apart to stabilize sediment and provide a windbreak effect. This information was given to us by Ahmed Pérez. He stated that these trees would be useful in protecting the coast because they are suited to high salt conditions (Personal Communication, 2019).
- Another possibility would be to plant coral offshore to create a natural break water and decrease the wave energy. We developed this recommendation by examining previous uses

of coral restoration in the San Juan Bay Estuary Climate Change Adaptation Plan and speaking with Regional Superintendent Antares Ramos Álvarez. (Bauzá-Ortega, 2015; Personal Communications, 2019). The coral can also serve as a habitat for aquatic life. Potential coral species include Elkhorn and Staghorn coral because they grow quickly to a large size and exhibit resilience. Coral should only be planted at locations of existing reefs, or else there is a risk of disrupting currents and causing unintended erosion elsewhere.
- Planting aquatic vegetation is another useful strategy: planting aquatic grasses can minimize wave energy at the beach, while also stabilizing sediment. Different areas such as the Chesapeake and Tampa Bays have utilized these strategies to protect the coast. (U.S. EPA, 2009).
- Let the natural systems retreat inland and adapt to the rising water levels. The practice of allowing coastal ecosystems to move inland is known as facilitating retreat, and the EPA has cited successful uses of this strategy in Buzzards Bay, Massachusetts (U.S. EPA, 2009). It is recommended here because there is not any infrastructure restricting beach retreat.

Langley Drive

- Due to the road's proximity to the Daguao River, Langley drive is in danger of flooding (Government of Puerto Rico, 2015). To reduce flooding from the Daguao River, constructing levees alongside the road could divert water elsewhere, which would reduce erosion. It may be necessary to accept that parts of this road will eventually be underwater due to river flooding. Langley Drive is a paved road in a more developed area. Because of this, we feel that the construction of levees is an appropriate strategy, even though it is more invasive than many of the other strategies (Australian Government Department of the Environment and Energy, 2019).

Boardwalk

- Santiago Oliver Báez described that the boardwalk is at risk due to flooding from the river, which would eliminate access to the observation tower (Personal Communication, 2019). Our research also revealed that it will be inundated after six feet of sea level rise (Government of Puerto Rico, 2015). During future renovations of the boardwalk, we recommend that it is raised higher to accommodate SLR and flooding like other infrastructure (Bauzá-Ortega, 2015).

5.2 Future Work

Because the implementation of climate change adaptation strategies has been limited in the Caribbean and Puerto Rico, monitoring the effects of adaptation strategies here will be important. Some strategies predicted to be effective may have unpredicted consequences, so the analysis of impacts can provide data for other areas with similar climates to more effectively adapt in the future. Furthermore, because climate model predictions are uncertain about the rate of sea level rise within the next 30-100 years, as the exact values are regional and dependent on global rates of greenhouse gas production and the climates response, monitoring the changes in sea level in Puerto Rico will provide important information for the local region and global data. It may be necessary to alter adaptation strategies to accommodate unexpected changes in sea level with time.

In addition, developing a method to connect adaptation strategies with ongoing projects and objectives by PLN, such as Project Habitat and the education of local communities, will expand awareness about the importance of climate change and how it can be combated. Along with the negative impacts of climate change, there is opportunity to expand our knowledge of how natural systems adapt. There are currently gaps in human knowledge which may be filled through observing the impacts of climate change in the coming years. For example, no one knows how climate change, and a more direct connection to the ocean, will affect the dinoflagellates in the bioluminescent lagoon. Another study to help increase our knowledge on natural systems, would involve observing how mangroves adapt to SLR in Puerto Rico. There have been studies on the mangrove's adaptation to SLR in other locations, but the results have been conflicting, furthermore little has been specifically researched in Puerto Rico and the Caribbean. This information will be important for unexpected climate change impacts, so that adaptation strategies can be altered to maintain effectiveness.

SLR projections outside of the boundary of Las Cabezas de San Juan Nature Reserve show that the government road PR-987 will be inundated at three feet of SLR. This would cut off access into the reserve. This amount of SLR may also impact the nursery and other infrastructure around the visitor center. We recommend that the vulnerability of this area be further evaluated. To maintain access in the natural reserve it will be important to work with the Puerto Rican government and local communities in order to implement adaptation strategies outside of the reserve so that the road PR-987 can maintain functionality in the coming years.

Other areas under the protection of PLN and throughout Puerto Rico will also be impacted by climate change. Through the application of the same methods outlined within this project, other at-risk areas may be assessed to provide a foundation to incorporate climate change adaptation into the next edition of site management plans. Globally, climate change is a major issue threatening both natural and manmade systems. Through climate change adaptation strategies, such as those outlined in our project, the damaging effects on ecosystems, infrastructure, cultural heritage sites can be reduced. We expect this project to be transferable into other regions that are struggling with impacts of climate change, especially those with extensive coastal zones.

References

Alibaba. (n.d.). Seaweed Baling Machine. Retrieved April 19, 2019, from https://www.alibaba.com/showroom/seaweed-baling-machine.html

Australian Government Department of the Environment and Energy. (2019). Climate change. Retrieved January 12, 2019, from http://www.environment.gov.au/climate-change

Bauzá-Ortega, J. (2015). *San Juan Bay Estuary Climate Change Adaptation Plan.* San Juan, PR: San Juan Bay Estuary Plan

Brian. (2013). Photos: Las Cabezas de San Juan Nature Reserve Tour. Retrieved from https://www.discoveringpuertorico.com/photos-la-cabezas-de-san-juan-tour-in-photos/

Bruin, K., Dellink, R., Ruijs, A., Bolwidt, L., Buuren, A., Graveland, J., . . . Ierland, E. C. (2009). Adapting to climate change in The Netherlands: An inventory of climate adaptation options and ranking of alternatives. *Climatic Change,95*(1-2), 23-45. doi:10.1007/s10584-009-9576-4

Cambers, G., (n.d.). Impacts of Climate Change on the Beaches of Puerto Rico. *University of Puerto Rico – Sea Grant College Program*. Retrieved from http://academic.uprm.edu/abe/ClimateChangePR/Climate%20change%20and%20beaches%20G.%20Cambers%20extended.doc

Caribbean Business. (2018, Sep 27,). Gov tells global tourism industry about Puerto Rico's potential as a tourism, investment destination. *Caribbean Business,* Retrieved from https://caribbeanbusiness.com/gov-tells-global-tourism-industry-about-puerto-ricos-potential-as-a-tourism-investment-destination/

Carrubba, L., Castañer, J.A., Chaparro, R., Crespo Acevedo, W.L., Diaz, E., Espinoza, R., et al. (2013). Climate Change and Puerto Rico's Society and Economy. Technical Report. Retrieved from http://pr-ccc.org/download/PR%20State%20of%20the%20Climate-WG3.pdf

Climate Impacts on Ecosystems. (2017, January 19). Retrieved from https://19january2017snapshot.epa.gov/climate-impacts/climate-impacts-ecosystems_.html

Conservation Trust of Puerto Rico. (2019). Retrieved from http://www.puertorico.com/blog/conservation-trust-of-puerto-rico/

Columbia University Mailman School of Public Health. (n.d.). Content Analysis. Retrieved March 19, 2019, from https://www.mailman.columbia.edu/research/population-health-methods/content-analysis

Cost Owl. (2019). 2019 Average Roof Sealant Application Costs. Retrieved April 18, 2019, from http://www.costowl.com/home-improvement/roof-sealant-cost.html

Dawson Foundation Repair. (n.d.). Cost of Elevating A House Above the Floodplain. Retrieved April 19, 2019, from https://www.dawsonfoundationrepair.com/cost-elevating-house/

Dawson, T. (2013). Erosion and coastal archeology: Evaluating threat and prioritising action. *Ancient Maritime Communities and the Relationship between People and Environment Along the European Atlantic Coasts*, 77-83. Retrieved from https://www.academia.edu/15184676/Erosion_and_coastal_archaeology_Evaluating_the_threat_and_prioritising_action_In_Ancient_Maritime_Communities_and_the_Relationship_between_People_and_Environment_along_the_European_Atlantic_Coasts_-_BAR_International_Series_2570?auto=download

Diaz, Ernesto L. and Jacobs, Kasey R. (2015), Proposed Amendment to the Puerto Rico Coastal Zone Management Program. (No. 80). Washington: Federal Information & News Dispatch, Inc. Retrieved from https://coast.noaa.gov/fellowship/pdfs/2014_PR.pdf

Dirt, gravel, and low volume road program: Typical costs (Rep.). (2015). PN: Penn. State Center for Dirt and Gravel Road Studies. Retrieved from https://www.dirtandgravel.psu.edu/sites/default/files/PA%20Program%20Resources/Program%20Specific%20Resources/Reference%20Material/Typical_DGLVRP_costs_4_2015.pdf

Environmental Protection Agency. (2018, December 10). Heat Island Effect. Retrieved February 3, 2019, from https://www.epa.gov/heat-islands

Eastern Research Group. (2013). What will adaptation cost? An economic framework for coastal community infrastructure. *Final Report, National Oceanic and Atmospheric Administration* (NOAA) Coastal Service Center.

Eriksson, J., & Juhl, A. (2012). *Guide to risk and vulnerability analyses* (Rep.). Swedish Civil Contingencies Agency. Retrieved from https://www.msb.se/ribdata/filer/pdf/26267.pdf

Estimated cost of seagrass restoration. (2001). Cambridge University Press. Retrieved from http://www.edc.uri.edu/restoration/html/tech_sci/socio/costable2.htm

Ezcurra, P., & Rivera-Collazo, I. (2018). An assessment of the impacts of climate change on Puerto Rico's cultural heritage with a case study on sea-level rise. *Journal of Cultural Heritage; Journal of Cultural Heritage, 32*, 198-209. doi: 10.1016/j.culher.2018.01.016

FEMA. (2007, March). *Selecting Appropriate Mitigation Measures for Flood-prone Structures* (Rep.). Retrieved April 18, 2019, from FEMA website: https://www.fema.gov/media-library-data/20130726-1609-20490-5083/fema_551.pdf

FEMA. (2018). Public assistance funding tops $3 billion for Puerto Rico. Retrieved from https://www.fema.gov/news-release/2018/08/07/fema-public-assistance-funding-tops-3-billion-puerto-rico

Fideicomiso de Conservación de Puerto Rico. (2010.a). *Plan de Manejo del Área Natural Protegida Medio Mundo y Daguao* (pp. 7-303, Rep.).

Fideicomiso de Conservación de Puerto Rico. (2010.b). *Reserva Natural Las Cabezas de San Juan Plan de Manejo* (pp. 17-146, Rep.).

Flood Zones. (n.d.). Retrieved April 12, 2019, from https://www.fema.gov/flood-zones

Goethals, H. (1991). The eye of the reserve. (las cabezas de san juan nature reserve) (column). *Americas (English Edition), 43*(1), 4.

Goreau, T. J., & Hilbertz, W. (2005). Marine Ecosystems Restoration: Costs and Benefits for Coral Reefs. *World Resource Review, 17,* 375-409. Retrieved from http://www.globalcoral.org/wp-content/uploads/2013/04/WRR_Goreau_Hilbertz_2005.pdf

Gould, W. A. et al. (2018). *Fourth national climate assessment: In impacts, risks, and adaptation in the united states: Chapter 20 - U.S. caribbean.* (No. 2). Washington, D.C.: US Global Change Research Program. doi:10.7930/NCA4. 2018.CH20

Government of Puerto Rico. (2015, December 10). Interactive Map of Puerto Rico [Computer software]. Retrieved March 13, 2019.

Greenfieldboyce, Nell (2007). Study: 634 Million People at Risk from Rising Seas. *NPR*, NPR, Retrieved from www.npr.org/templates/story/story.php?storyId=9162438.

Gross, J. E., Watson, J. E., Welling, L. A., & Woodley, S. (2016). *Adapting to Climate Change* (Rep.). Retrieved March 22, 2019, from International Union for Conservation of Nature website: https://www.iucn.org/content/adapting-climate-change-0

Haugen, A., & Mattsson, J. (2011). Preparations for climate change's influences on cultural heritage. *International Journal of Climate Change Strategies and Management*, *3*(4), 386–401. https://doi.org/10.1108/17568691111175678

Impacts on Mangroves. (2018, October 03). South Florida Aquatic Environments. Retrieved from https://www.floridamuseum.ufl.edu/southflorida/habitats/mangroves/impacts/

International Union for Conservation of Nature. (2019, March 22). About. Retrieved from https://www.iucn.org/about

IPCC. (2008). *Climate Change 2007 Synthesis Report* (Rep.). Retrieved https://www.ipcc.ch/site/assets/uploads/2018/02/ar4_syr_full_report.pdf

IPCC. (2018). *Summary for policymakers. In: Global warming of 1.5°C*. World Meteorological Organization, Geneva, Switzerland.

Mangroves help protect against sea level rise. (2015, July 29). *Space Daily*. Retrieved from http://link.galegroup.com.ezproxy.wpi.edu/apps/doc/A423476377/ITOF?u=mlin_c_worpoly&sid=ITOF&xid=981c90cf

Martín, B., Ortega, E., Otero, I., & Arce, R. M. (2016). Landscape character assessment with GIS using map-based indicators and photographs in the relationship between landscape and roads. *Journal of Environmental Management*, *180*, 324-334. doi: 10.1016/j.jenvman.2016.05.044

Mazzei, P. (2018, Feb 8,). What Puerto Rico is, and isn't, getting in disaster relief. Retrieved from https://www.nytimes.com/2018/02/08/us/puerto-rico-disaster-relief.html

Medio Mundo y Daguao. (n.d.). Retrieved from https://www.paralanaturaleza.org/en/medio-mundo-y-daguao-eng-2/

Methods for economic analysis of climate change adaptation interventions. (2013). Retrieved from https://www.climatelinks.org/sites/default/files/asset/document/Methods%2520of%2520Economic%2520Analysis_CLEARED.pdf

Moore, S., Brown, G., Kobryn, H., & Strickland-Munro, J. (2017). Identifying conflict potential in a coastal and marine environment using participatory mapping. *Journal of Environmental Management*, *197*, 706–718. https://doi.org/10.1016/j.jenvman.2016.12.026

Munaretto, S., Vellinga, P., & Tobi, H. (2012). Flood protection in Venice under conditions of sea-level rise: an analysis of institutional and technical measures. *Coastal Management*, *40*(4), 355–380. https://doi.org/10.1080/08920753.2012.692311

National Park Service. (2016). *Climate change impacts on cultural resources* (tech.). Climate Change Response Program.

Natural wood snow/sand fence. (n.d.). Retrieved from http://www.mutualindustries.com/product/natural-wood-snowsand-fence

NCCARF. (2019). CoastAdapt. Retrieved February 3, 2019, from https://coastadapt.com.au/

Nguyen Hai. (2012). The Eisenhower method: What is it? Retrieved from https://appfluence.com/productivity/what-is-the-eisenhower-method/

NOAA. (2019, February). Climate Change Impacts. Retrieved April 24, 2019, from https://www.noaa.gov/education/resource-collections/climate-education-resources/climate-change-impacts

NOAA Office for Coastal Management. (n.d.). DigitalCoast. Retrieved February 6, 2019, from https://coast.noaa.gov/digitalcoast/tools/slr

Page, C. A., Muller, E. M., & Vaughn, D. E. (2018). Microfragmenting for the successful restoration of slow growing massive corals. *Ecological Engineering*, *123*, 86-94. doi:https://doi.org/10.1016/j.ecoleng.2018.08.017.

Para la Naturaleza, The conservation trust of Puerto Rico launches Para la Naturaleza. (n.d.) Retrieved from https://www.paralanaturaleza.org/en/conservation-trust-of-puerto-rico-launches-para-la-naturaleza/

Para la Naturaleza - who are we? (n.d) Retrieved from https://www.paralanaturaleza.org/en/who-are-we/

Para la Naturaleza. (2019). Retrieved from https://www.linkedin.com/company/para-la-naturaleza/about/

Para la Naturaleza. (n.d). Protected Areas. Retrieved March 26, 2019, from https://www.paralanaturaleza.org/en/category/about-us/protected-areas/

Para la Naturaleza annual report (2016). Para la Naturaleza. Retrieved from https://www.paralanaturaleza.org/dl/PLN-Annual-Report-2016.pdf

Prioritization matrix: QI toolbox. (n.d). Retrieved from http://www.health.state.mn.us/divs/opi/qi/toolbox/prioritizationmatrix.html

Puerto Rico Climate Change Council. (2013.) Puerto Rico’s state of the climate 2010-2013: Assessing Puerto Rico’s social-ecological vulnerabilities in a changing climate. Puerto Rico Coastal Zone Management Program, Department of Natural and Environmental Resources, NOAA Office of Ocean and Coastal Resource Management. San Juan, PR.

Puerto Rico Climate Change Council. (2015). Ruta hacia la resiliencia: Guía de estrategias para la adaptación a los cambios climáticos. Programa de Manejo de la Zona Costanera.

Puerto Rico at the forefront of climate resiliency. (2018). Retrieved from http://prfaa.pr.gov/puerto-rico-at-the-forefront-of-climate-resiliency/

Puerto Rico tourism company. (2019). Retrieved from https://www.prtourism.com/dnn/About-Us

Rashband, W. (2018, July 11). ImageJ [Computer software]. Retrieved from https://imagej.nih.gov/ij/download.html

Restoration of Seagrass Meadows. (n.d.). OCEANA. Retrieved from https://www.saveposidoniaproject.org/formentera/wp-content/uploads/2017/03/OCEANA_Restoration_of_seagrass_meadows.pdf

Revel, Danièle. (2014). Climate change 2014: Impacts, adaptation and vulnerability. Retrieved from http://energieclimat.hypotheses.org/20557

Spurgeon, J. (2001). Improving the economic effectiveness of coral reef restoration. *Bulletin of Marine Science*, *69*, 1031-1045.

Talty, A. (2018, Sep 30). How Puerto Rico is using tourism to rebuild after hurricane Maria. *Forbes*, Retrieved from https://www.forbes.com/sites/alexandratalty/2018/09/30/how-puerto-rico-is-using-tourism-to-rebuild-after-hurricane-maria/#5d0bbb469962

The Commonwealth of Massachusetts. (2018, December). *StormSmart Properties Fact Sheet 6: Sand Fencing* (Rep.). Retrieved April 19, 2019, from The Government of Massachusetts website: https://www.mass.gov/files/documents/2018/05/29/ssp-factsheet-6-sandfencing-new.pdf

Titus, G. James. (2011). *Rolling easements*. Washington, D.C.: U.S. Environmental Protection Agency. Retrieved from https://www.epa.gov/sites/production/files/documents/rollingeasementsprimer.pdf

Tompkins, E., & Adger, W. (2004). Does adaptive management of natural resources enhance resilience to climate change? *Ecology and Society, 9*(2). Retrieved from http://www.jstor.org/stable/26267677

South Florida Plant Guide. (n.d.). Sea grape. Retrieved from https://www.south-florida-plant-guide.com/sea-grape.html

Spalding M., McIvor A., Tonneijck F.H., Tol S., and Van Eijk P. (2014). Mangroves for coastal defense. Guidelines for coastal managers & policy makers. Published by Wetlands International and The Nature Conservancy. 42 p

U.S. EPA (2009). *Synthesis of adaptation options for coastal areas*. Washington, D.C.: U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Water. Retrieved from https://www.epa.gov/sites/production/files/2014-04/documents/cre_synthesis_1-09.pdf

Van Aalst, M. K. (2006), The impacts of climate change on the risk of natural disasters. Disasters, 30: 5-18. doi:10.1111/j.1467-9523.2006.00303.x

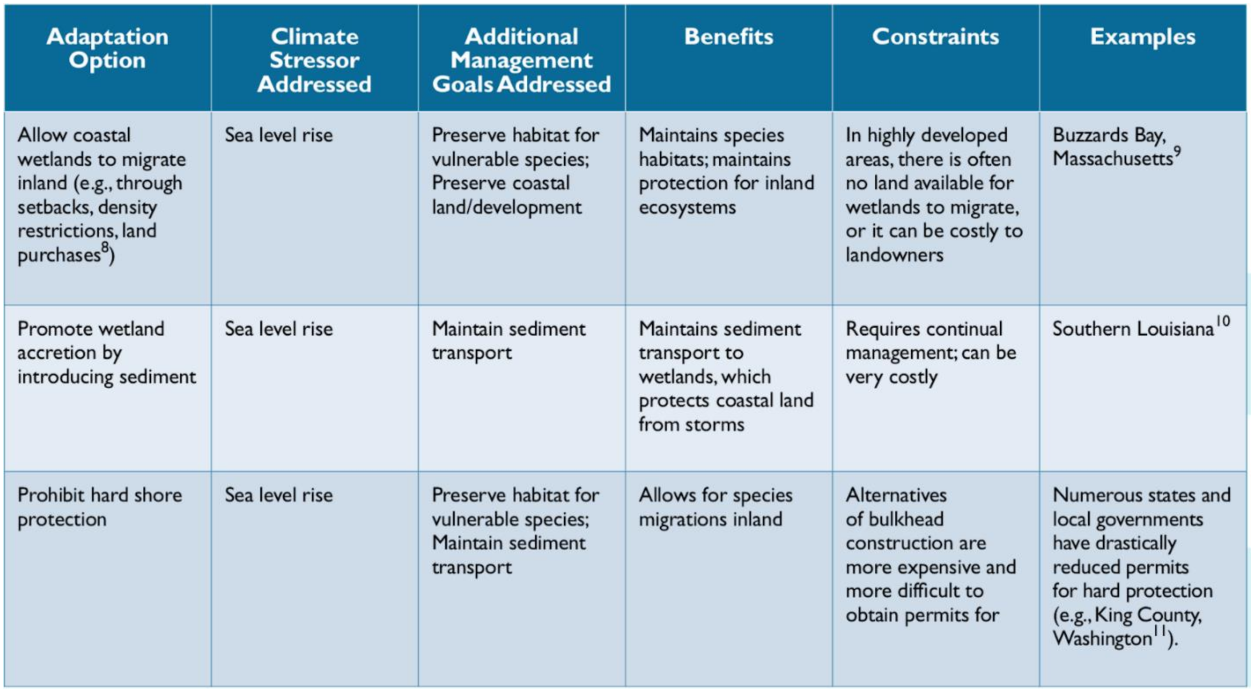
Von Schorlemer, S., & Maus, S. (Eds.). (2014). *Climate Change as a Threat to Peace: Impacts on Cultural Heritage and Cultural Diversity*. Frankfurt am Main: Peter Lang AG. Retrieved from http://www.jstor.org/stable/j.ctv2t4cvp

Weaver, P. L., Coll Rivera, J., L., Ramirez, J. L., & International Institute of, Tropical Forestry. (1999). *Las cabezas de san juan nature reserve (el faro)* U.S. Dept. of Agriculture, Forest Service, International Institute of Tropical Forestry

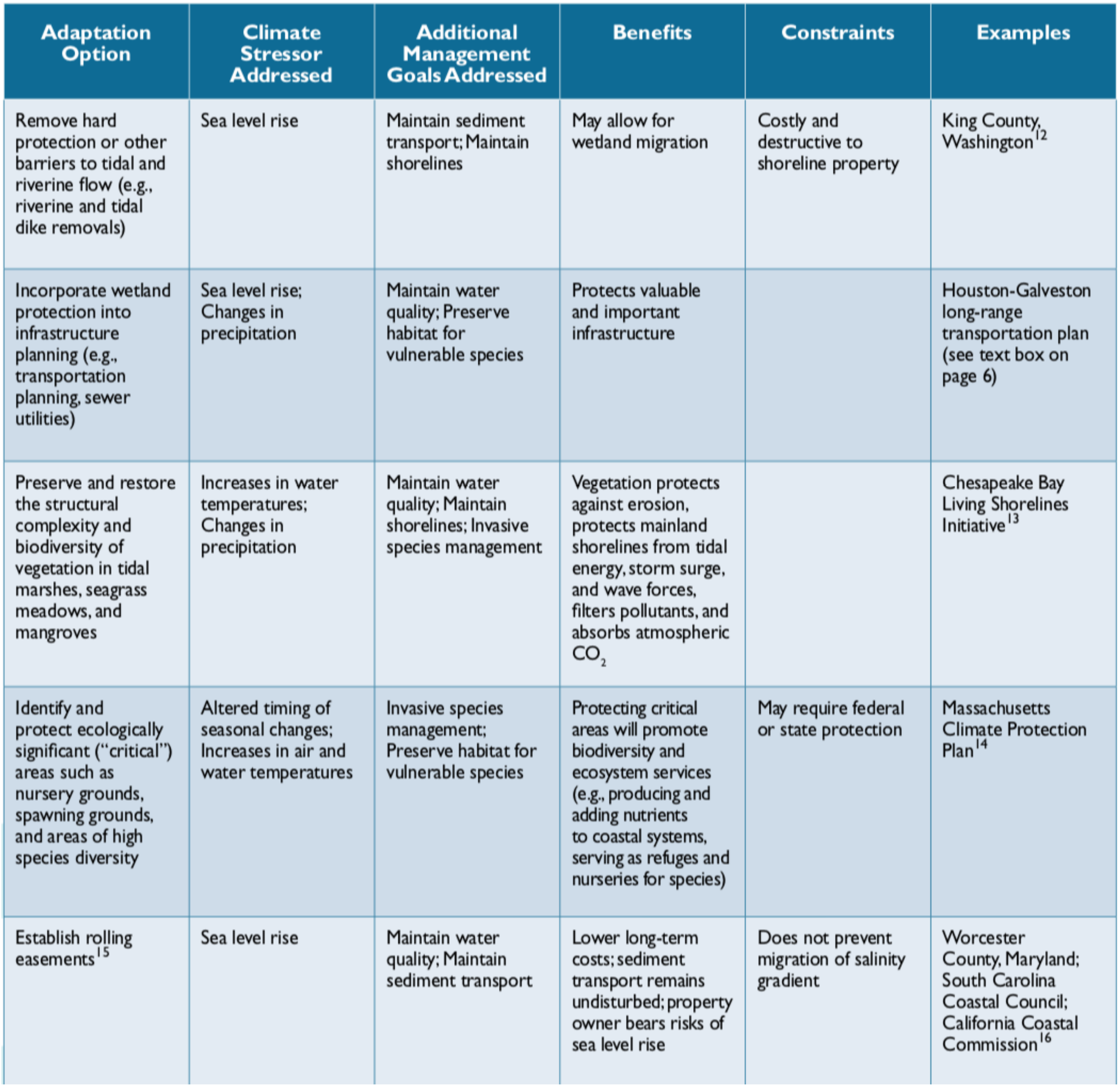
World Wildlife Foundation. (2017). The Effects of Climate Change. Retrieved from https://www.wwf.org.uk/effectsofclimatechange

Appendix A: Environmental Protection Agency Adaptation Options

A.1 Adaptation Options for Maintaining/Restoring Wetlands

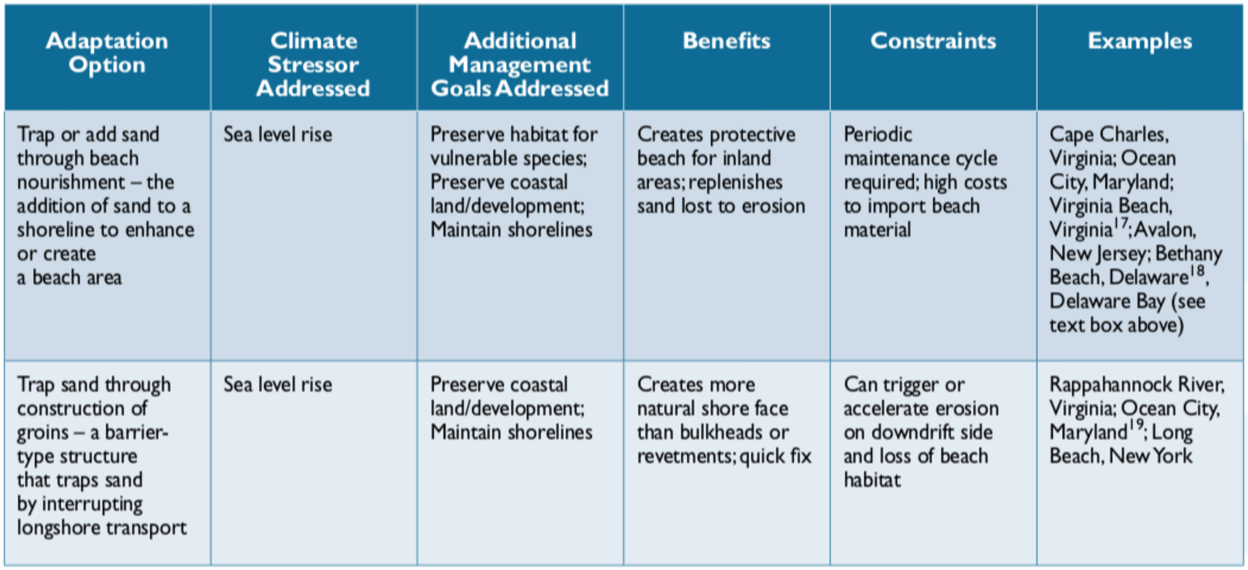


Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Allow coastal wetlands to migrate inland (e.g., through setbacks, density restrictions, land purchases[8])	Sea level rise	Preserve habitat for vulnerable species; Preserve coastal land/development	Maintains species habitats; maintains protection for inland ecosystems	In highly developed areas, there is often no land available for wetlands to migrate, or it can be costly to landowners	Buzzards Bay, Massachusetts[9]
Promote wetland accretion by introducing sediment	Sea level rise	Maintain sediment transport	Maintains sediment transport to wetlands, which protects coastal land from storms	Requires continual management; can be very costly	Southern Louisiana[10]
Prohibit hard shore protection	Sea level rise	Preserve habitat for vulnerable species; Maintain sediment transport	Allows for species migrations inland	Alternatives of bulkhead construction are more expensive and more difficult to obtain permits for	Numerous states and local governments have drastically reduced permits for hard protection (e.g., King County, Washington[11]).

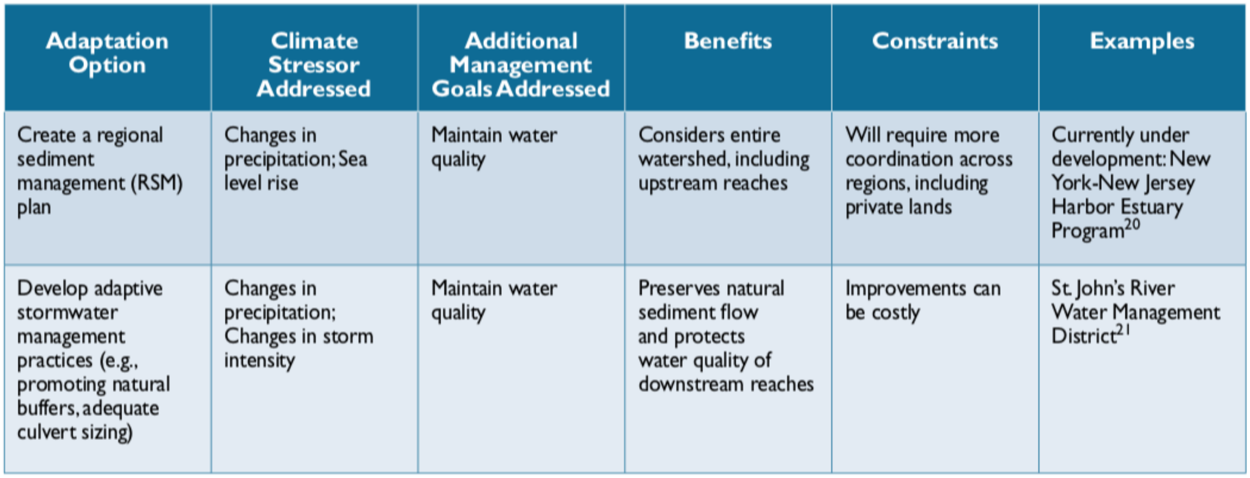


Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Remove hard protection or other barriers to tidal and riverine flow (e.g., riverine and tidal dike removals)	Sea level rise	Maintain sediment transport; Maintain shorelines	May allow for wetland migration	Costly and destructive to shoreline property	King County, Washington[12]
Incorporate wetland protection into infrastructure planning (e.g., transportation planning, sewer utilities)	Sea level rise; Changes in precipitation	Maintain water quality; Preserve habitat for vulnerable species	Protects valuable and important infrastructure		Houston-Galveston long-range transportation plan (see text box on page 6)
Preserve and restore the structural complexity and biodiversity of vegetation in tidal marshes, seagrass meadows, and mangroves	Increases in water temperatures; Changes in precipitation	Maintain water quality; Maintain shorelines; Invasive species management	Vegetation protects against erosion, protects mainland shorelines from tidal energy, storm surge, and wave forces, filters pollutants, and absorbs atmospheric CO_2		Chesapeake Bay Living Shorelines Initiative[13]
Identify and protect ecologically significant ("critical") areas such as nursery grounds, spawning grounds, and areas of high species diversity	Altered timing of seasonal changes; Increases in air and water temperatures	Invasive species management; Preserve habitat for vulnerable species	Protecting critical areas will promote biodiversity and ecosystem services (e.g., producing and adding nutrients to coastal systems, serving as refuges and nurseries for species)	May require federal or state protection	Massachusetts Climate Protection Plan[14]
Establish rolling easements[15]	Sea level rise	Maintain water quality; Maintain sediment transport	Lower long-term costs; sediment transport remains undisturbed; property owner bears risks of sea level rise	Does not prevent migration of salinity gradient	Worcester County, Maryland; South Carolina Coastal Council; California Coastal Commission[16]

A.2 Adaptation Options for Maintaining Sediment Transport

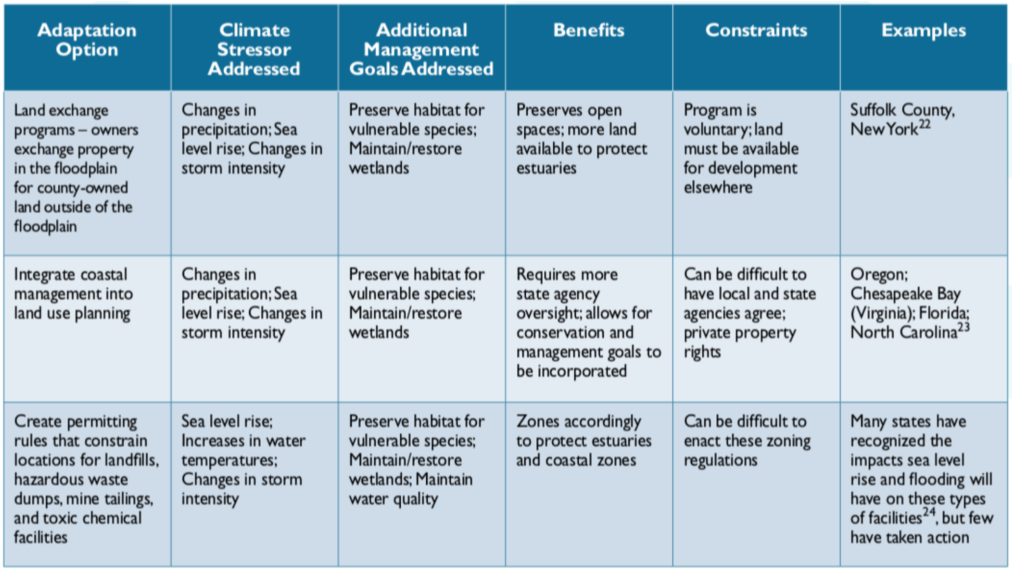


Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Trap or add sand through beach nourishment – the addition of sand to a shoreline to enhance or create a beach area	Sea level rise	Preserve habitat for vulnerable species; Preserve coastal land/development; Maintain shorelines	Creates protective beach for inland areas; replenishes sand lost to erosion	Periodic maintenance cycle required; high costs to import beach material	Cape Charles, Virginia; Ocean City, Maryland; Virginia Beach, Virginia[17]; Avalon, New Jersey; Bethany Beach, Delaware[18], Delaware Bay (see text box above)
Trap sand through construction of groins – a barrier-type structure that traps sand by interrupting longshore transport	Sea level rise	Preserve coastal land/development; Maintain shorelines	Creates more natural shore face than bulkheads or revetments; quick fix	Can trigger or accelerate erosion on downdrift side and loss of beach habitat	Rappahannock River, Virginia; Ocean City, Maryland[19]; Long Beach, New York

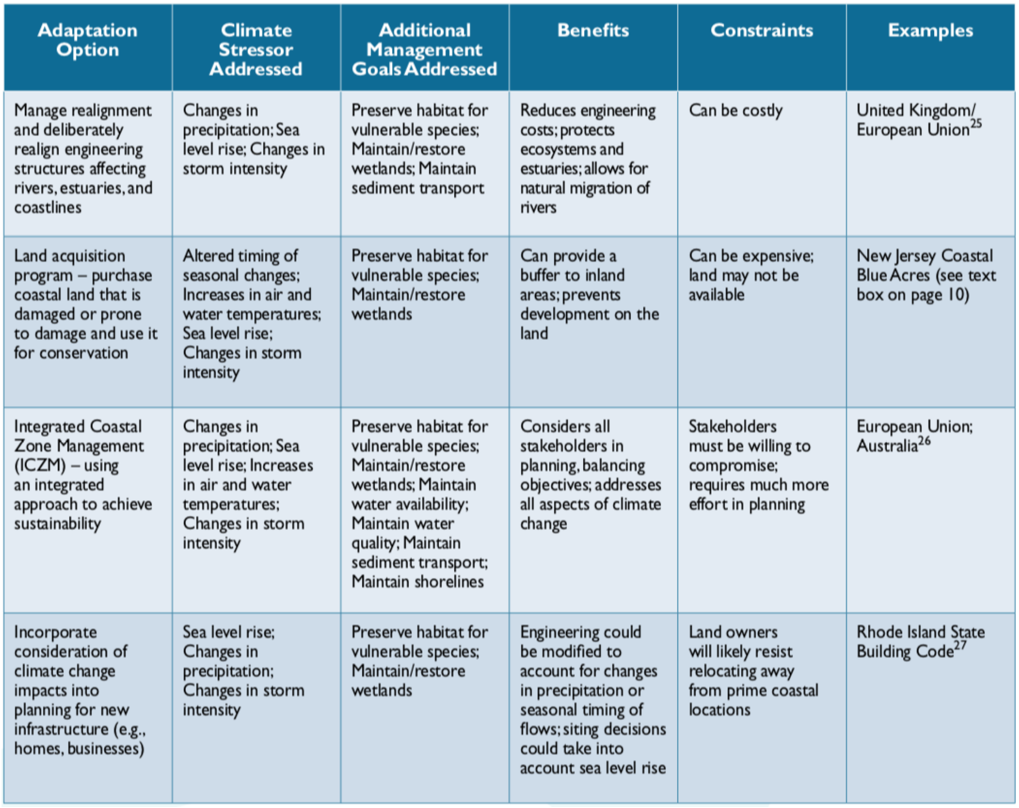


Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Create a regional sediment management (RSM) plan	Changes in precipitation; Sea level rise	Maintain water quality	Considers entire watershed, including upstream reaches	Will require more coordination across regions, including private lands	Currently under development: New York-New Jersey Harbor Estuary Program[20]
Develop adaptive stormwater management practices (e.g., promoting natural buffers, adequate culvert sizing)	Changes in precipitation; Changes in storm intensity	Maintain water quality	Preserves natural sediment flow and protects water quality of downstream reaches	Improvements can be costly	St. John's River Water Management District[21]

A.3 Adaptation Options for Preserving Coastal Land/Development (incl. Infrastructure)

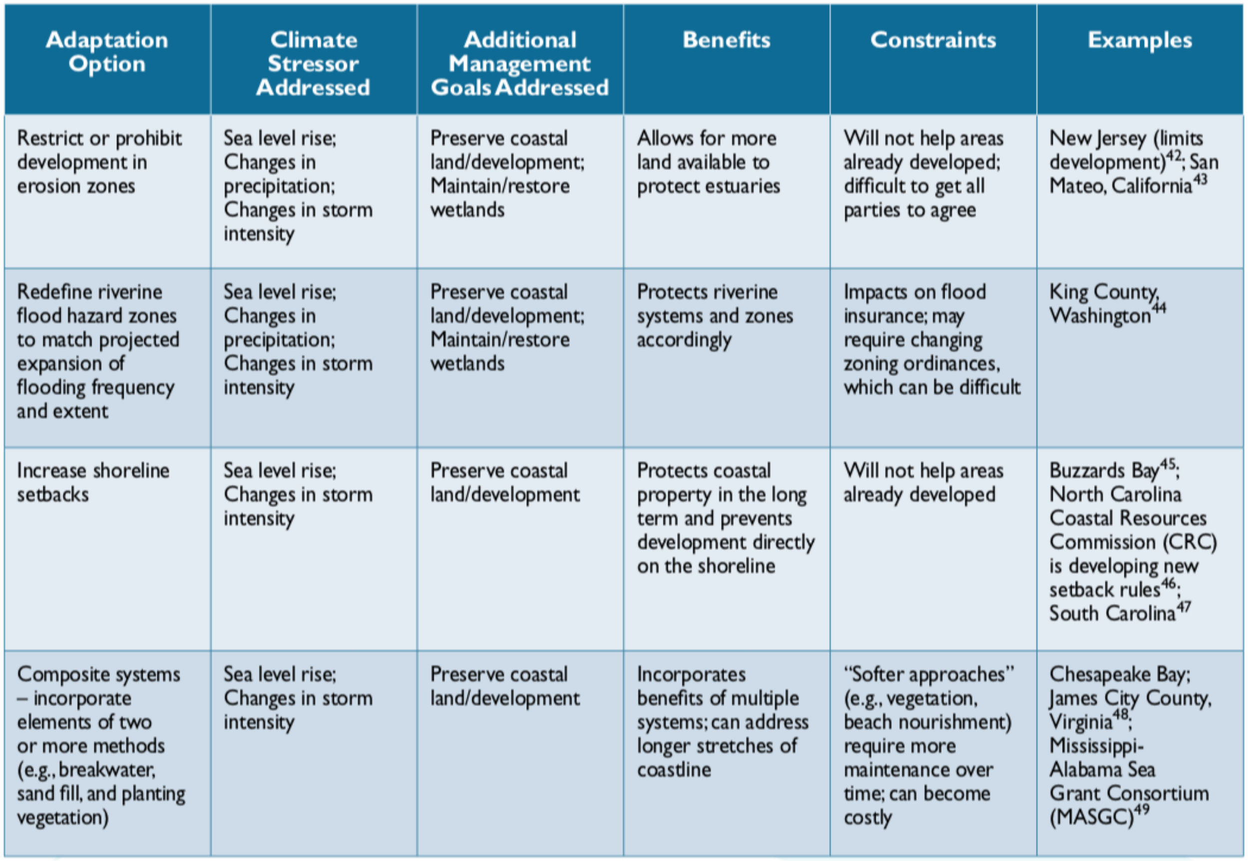


Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Land exchange programs – owners exchange property in the floodplain for county-owned land outside of the floodplain	Changes in precipitation; Sea level rise; Changes in storm intensity	Preserve habitat for vulnerable species; Maintain/restore wetlands	Preserves open spaces; more land available to protect estuaries	Program is voluntary; land must be available for development elsewhere	Suffolk County, New York[22]
Integrate coastal management into land use planning	Changes in precipitation; Sea level rise; Changes in storm intensity	Preserve habitat for vulnerable species; Maintain/restore wetlands	Requires more state agency oversight; allows for conservation and management goals to be incorporated	Can be difficult to have local and state agencies agree; private property rights	Oregon; Chesapeake Bay (Virginia); Florida; North Carolina[23]
Create permitting rules that constrain locations for landfills, hazardous waste dumps, mine tailings, and toxic chemical facilities	Sea level rise; Increases in water temperatures; Changes in storm intensity	Preserve habitat for vulnerable species; Maintain/restore wetlands; Maintain water quality	Zones accordingly to protect estuaries and coastal zones	Can be difficult to enact these zoning regulations	Many states have recognized the impacts sea level rise and flooding will have on these types of facilities[24], but few have taken action

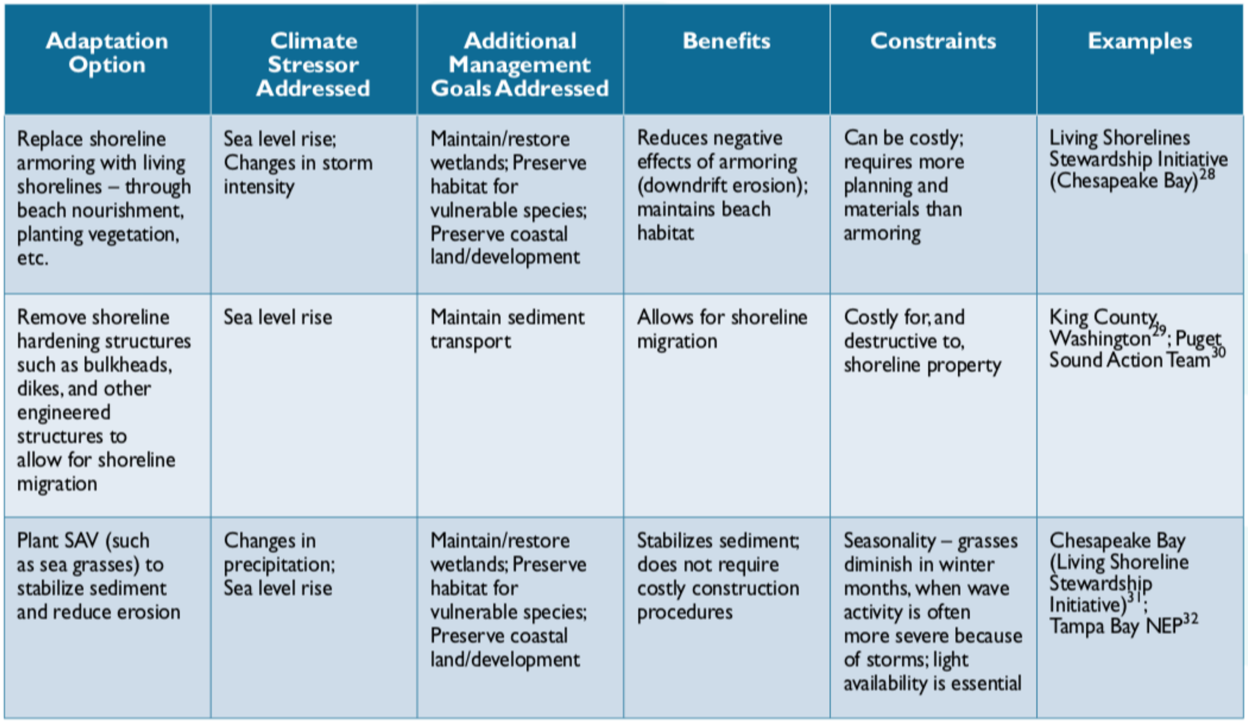


Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Manage realignment and deliberately realign engineering structures affecting rivers, estuaries, and coastlines	Changes in precipitation; Sea level rise; Changes in storm intensity	Preserve habitat for vulnerable species; Maintain/restore wetlands; Maintain sediment transport	Reduces engineering costs; protects ecosystems and estuaries; allows for natural migration of rivers	Can be costly	United Kingdom/ European Union[25]
Land acquisition program – purchase coastal land that is damaged or prone to damage and use it for conservation	Altered timing of seasonal changes; Increases in air and water temperatures; Sea level rise; Changes in storm intensity	Preserve habitat for vulnerable species; Maintain/restore wetlands	Can provide a buffer to inland areas; prevents development on the land	Can be expensive; land may not be available	New Jersey Coastal Blue Acres (see text box on page 10)
Integrated Coastal Zone Management (ICZM) – using an integrated approach to achieve sustainability	Changes in precipitation; Sea level rise; Increases in air and water temperatures; Changes in storm intensity	Preserve habitat for vulnerable species; Maintain/restore wetlands; Maintain water availability; Maintain water quality; Maintain sediment transport; Maintain shorelines	Considers all stakeholders in planning, balancing objectives; addresses all aspects of climate change	Stakeholders must be willing to compromise; requires much more effort in planning	European Union; Australia[26]
Incorporate consideration of climate change impacts into planning for new infrastructure (e.g., homes, businesses)	Sea level rise; Changes in precipitation; Changes in storm intensity	Preserve habitat for vulnerable species; Maintain/restore wetlands	Engineering could be modified to account for changes in precipitation or seasonal timing of flows; siting decisions could take into account sea level rise	Land owners will likely resist relocating away from prime coastal locations	Rhode Island State Building Code[27]

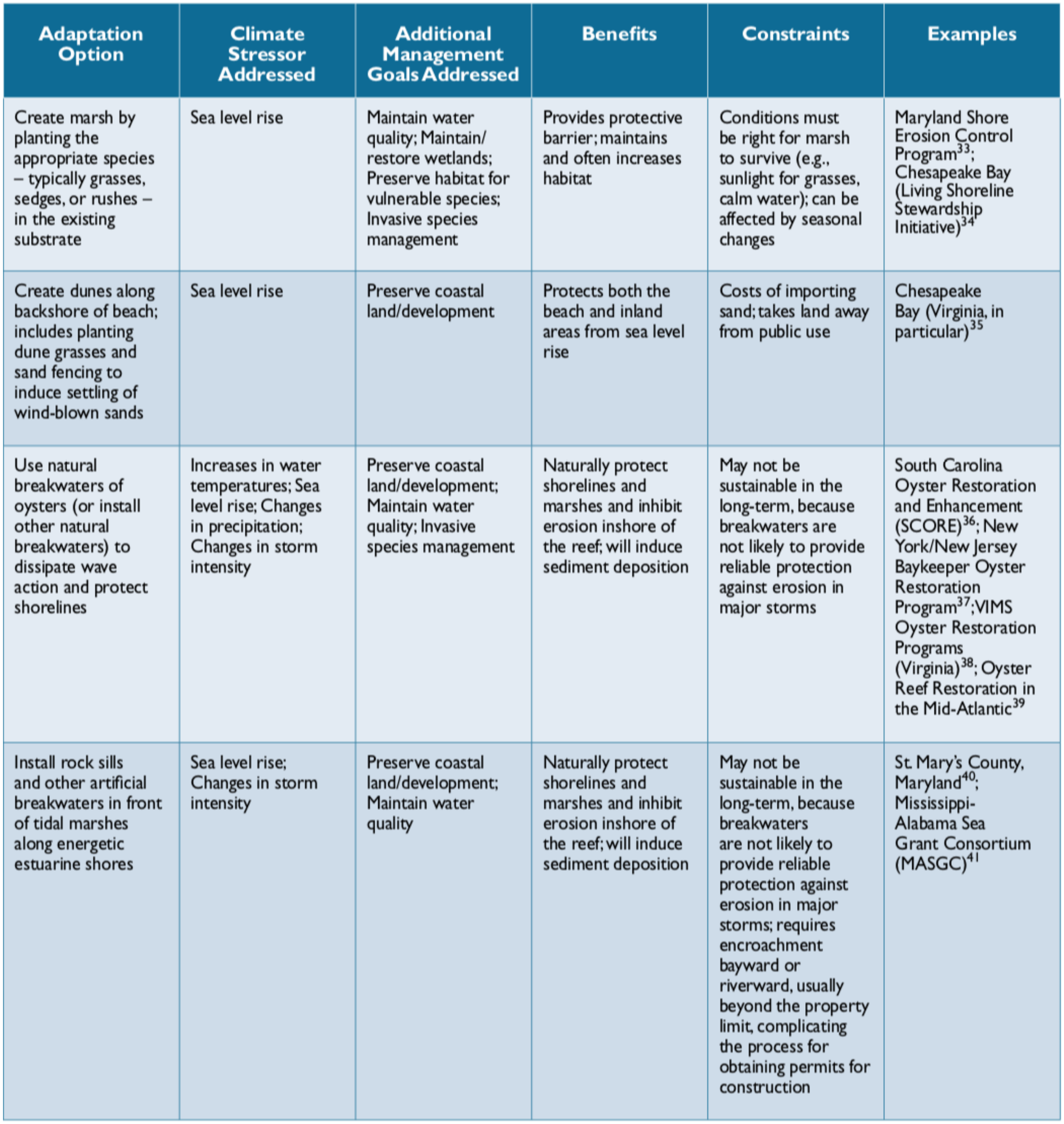
A.4 Adaptation Options for Maintaining Shorelines through "Soft" Measures



Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Restrict or prohibit development in erosion zones	Sea level rise; Changes in precipitation; Changes in storm intensity	Preserve coastal land/development; Maintain/restore wetlands	Allows for more land available to protect estuaries	Will not help areas already developed; difficult to get all parties to agree	New Jersey (limits development)[42]; San Mateo, California[43]
Redefine riverine flood hazard zones to match projected expansion of flooding frequency and extent	Sea level rise; Changes in precipitation; Changes in storm intensity	Preserve coastal land/development; Maintain/restore wetlands	Protects riverine systems and zones accordingly	Impacts on flood insurance; may require changing zoning ordinances, which can be difficult	King County, Washington[44]
Increase shoreline setbacks	Sea level rise; Changes in storm intensity	Preserve coastal land/development	Protects coastal property in the long term and prevents development directly on the shoreline	Will not help areas already developed	Buzzards Bay[45]; North Carolina Coastal Resources Commission (CRC) is developing new setback rules[46]; South Carolina[47]
Composite systems – incorporate elements of two or more methods (e.g., breakwater, sand fill, and planting vegetation)	Sea level rise; Changes in storm intensity	Preserve coastal land/development	Incorporates benefits of multiple systems; can address longer stretches of coastline	"Softer approaches" (e.g., vegetation, beach nourishment) require more maintenance over time; can become costly	Chesapeake Bay; James City County, Virginia[48]; Mississippi-Alabama Sea Grant Consortium (MASGC)[49]

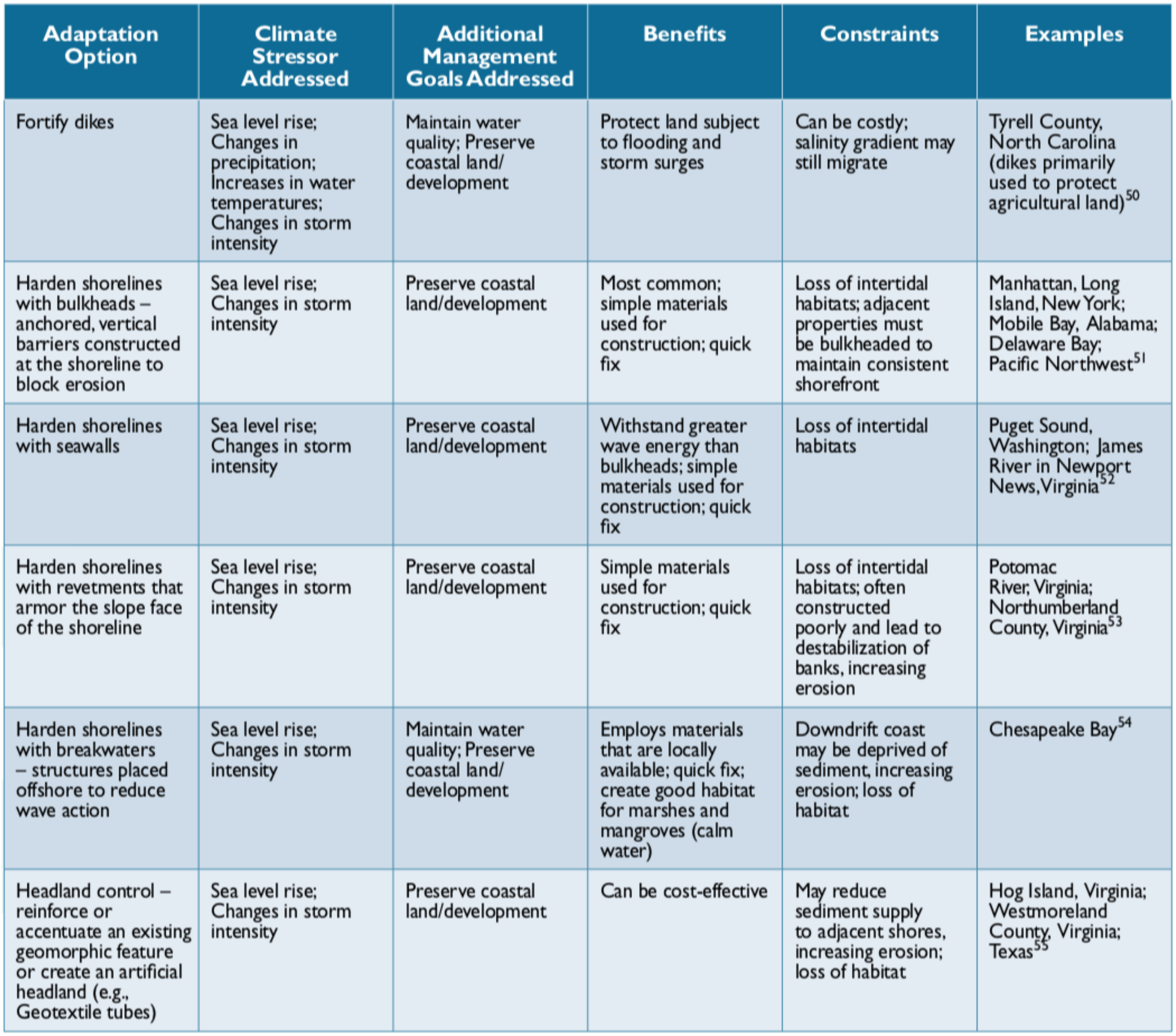


Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Replace shoreline armoring with living shorelines – through beach nourishment, planting vegetation, etc.	Sea level rise; Changes in storm intensity	Maintain/restore wetlands; Preserve habitat for vulnerable species; Preserve coastal land/development	Reduces negative effects of armoring (downdrift erosion); maintains beach habitat	Can be costly; requires more planning and materials than armoring	Living Shorelines Stewardship Initiative (Chesapeake Bay)[28]
Remove shoreline hardening structures such as bulkheads, dikes, and other engineered structures to allow for shoreline migration	Sea level rise	Maintain sediment transport	Allows for shoreline migration	Costly for, and destructive to, shoreline property	King County, Washington[29]; Puget Sound Action Team[30]
Plant SAV (such as sea grasses) to stabilize sediment and reduce erosion	Changes in precipitation; Sea level rise	Maintain/restore wetlands; Preserve habitat for vulnerable species; Preserve coastal land/development	Stabilizes sediment; does not require costly construction procedures	Seasonality – grasses diminish in winter months, when wave activity is often more severe because of storms; light availability is essential	Chesapeake Bay (Living Shoreline Stewardship Initiative)[31]; Tampa Bay NEP[32]



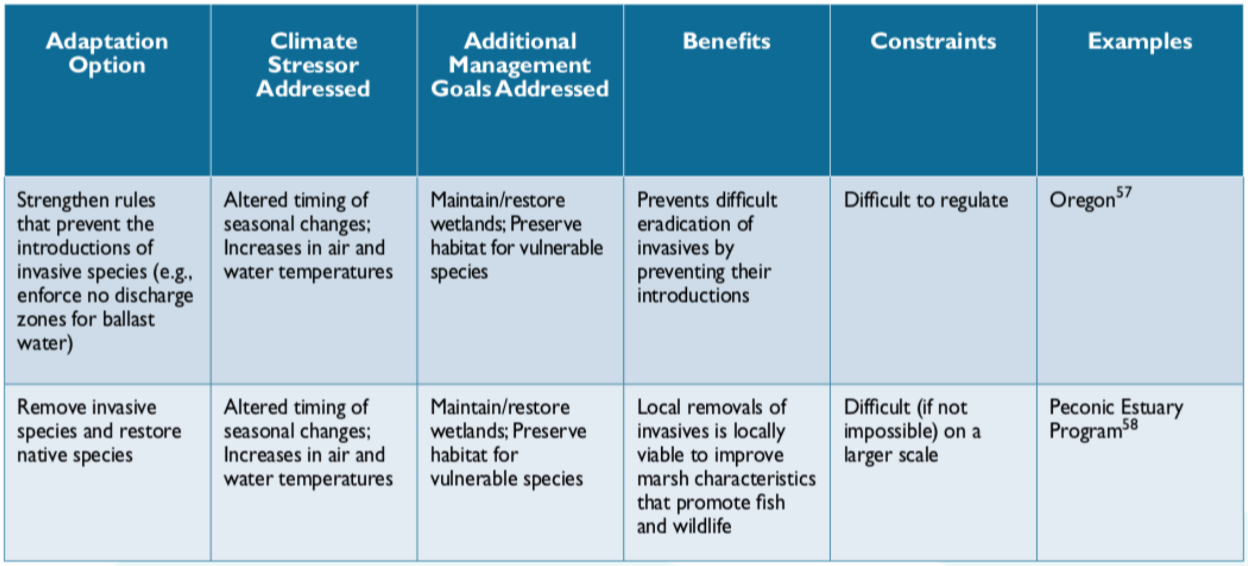
Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Create marsh by planting the appropriate species – typically grasses, sedges, or rushes – in the existing substrate	Sea level rise	Maintain water quality; Maintain/ restore wetlands; Preserve habitat for vulnerable species; Invasive species management	Provides protective barrier; maintains and often increases habitat	Conditions must be right for marsh to survive (e.g., sunlight for grasses, calm water); can be affected by seasonal changes	Maryland Shore Erosion Control Program[33]; Chesapeake Bay (Living Shoreline Stewardship Initiative)[34]
Create dunes along backshore of beach; includes planting dune grasses and sand fencing to induce settling of wind-blown sands	Sea level rise	Preserve coastal land/development	Protects both the beach and inland areas from sea level rise	Costs of importing sand; takes land away from public use	Chesapeake Bay (Virginia, in particular)[35]
Use natural breakwaters of oysters (or install other natural breakwaters) to dissipate wave action and protect shorelines	Increases in water temperatures; Sea level rise; Changes in precipitation; Changes in storm intensity	Preserve coastal land/development; Maintain water quality; Invasive species management	Naturally protect shorelines and marshes and inhibit erosion inshore of the reef; will induce sediment deposition	May not be sustainable in the long-term, because breakwaters are not likely to provide reliable protection against erosion in major storms	South Carolina Oyster Restoration and Enhancement (SCORE)[36]; New York/New Jersey Baykeeper Oyster Restoration Program[37]; VIMS Oyster Restoration Programs (Virginia)[38]; Oyster Reef Restoration in the Mid-Atlantic[39]
Install rock sills and other artificial breakwaters in front of tidal marshes along energetic estuarine shores	Sea level rise; Changes in storm intensity	Preserve coastal land/development; Maintain water quality	Naturally protect shorelines and marshes and inhibit erosion inshore of the reef; will induce sediment deposition	May not be sustainable in the long-term, because breakwaters are not likely to provide reliable protection against erosion in major storms; requires encroachment bayward or riverward, usually beyond the property limit, complicating the process for obtaining permits for construction	St. Mary's County, Maryland[40]; Mississippi-Alabama Sea Grant Consortium (MASGC)[41]

A.5 Adaptation Options for Maintaining Shorelines through "Hard" Measures



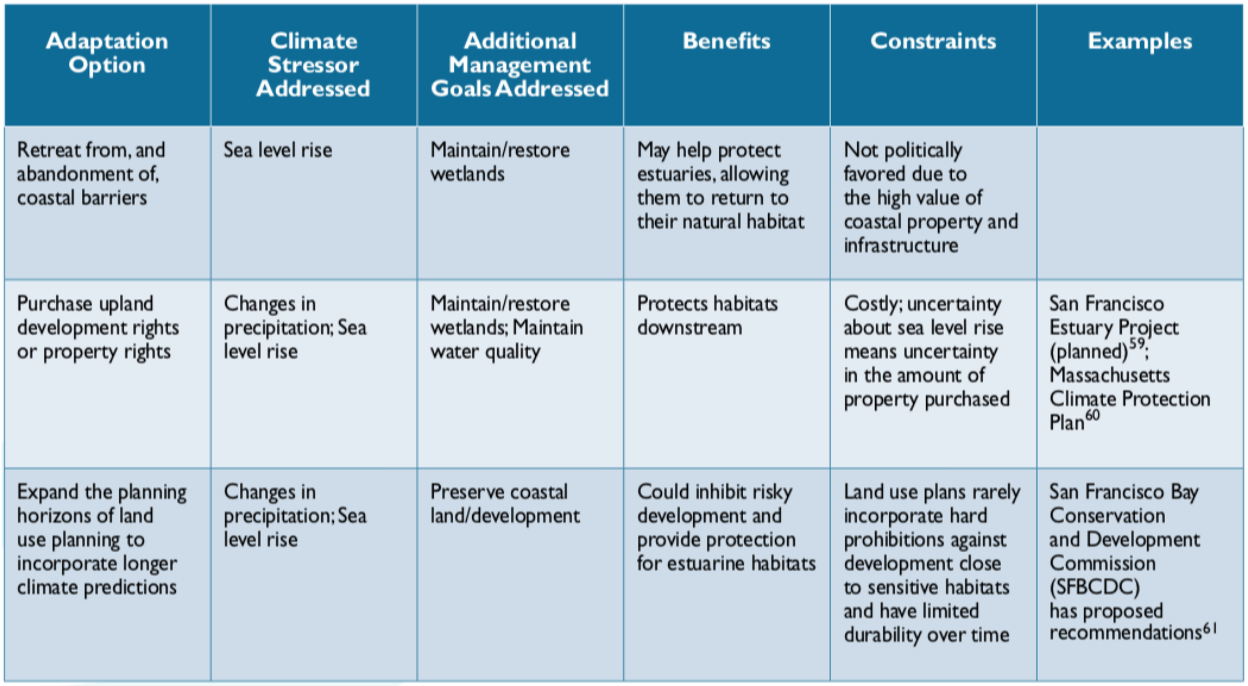
Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Fortify dikes	Sea level rise; Changes in precipitation; Increases in water temperatures; Changes in storm intensity	Maintain water quality; Preserve coastal land/ development	Protect land subject to flooding and storm surges	Can be costly; salinity gradient may still migrate	Tyrell County, North Carolina (dikes primarily used to protect agricultural land)[50]
Harden shorelines with bulkheads – anchored, vertical barriers constructed at the shoreline to block erosion	Sea level rise; Changes in storm intensity	Preserve coastal land/development	Most common; simple materials used for construction; quick fix	Loss of intertidal habitats; adjacent properties must be bulkheaded to maintain consistent shorefront	Manhattan, Long Island, New York; Mobile Bay, Alabama; Delaware Bay; Pacific Northwest[51]
Harden shorelines with seawalls	Sea level rise; Changes in storm intensity	Preserve coastal land/development	Withstand greater wave energy than bulkheads; simple materials used for construction; quick fix	Loss of intertidal habitats	Puget Sound, Washington; James River in Newport News, Virginia[52]
Harden shorelines with revetments that armor the slope face of the shoreline	Sea level rise; Changes in storm intensity	Preserve coastal land/development	Simple materials used for construction; quick fix	Loss of intertidal habitats; often constructed poorly and lead to destabilization of banks, increasing erosion	Potomac River, Virginia; Northumberland County, Virginia[53]
Harden shorelines with breakwaters – structures placed offshore to reduce wave action	Sea level rise; Changes in storm intensity	Maintain water quality; Preserve coastal land/ development	Employs materials that are locally available; quick fix; create good habitat for marshes and mangroves (calm water)	Downdrift coast may be deprived of sediment, increasing erosion; loss of habitat	Chesapeake Bay[54]
Headland control – reinforce or accentuate an existing geomorphic feature or create an artificial headland (e.g., Geotextile tubes)	Sea level rise; Changes in storm intensity	Preserve coastal land/development	Can be cost-effective	May reduce sediment supply to adjacent shores, increasing erosion; loss of habitat	Hog Island, Virginia; Westmoreland County, Virginia; Texas[55]

A.6 Adaptation Options for Invasive Species Management

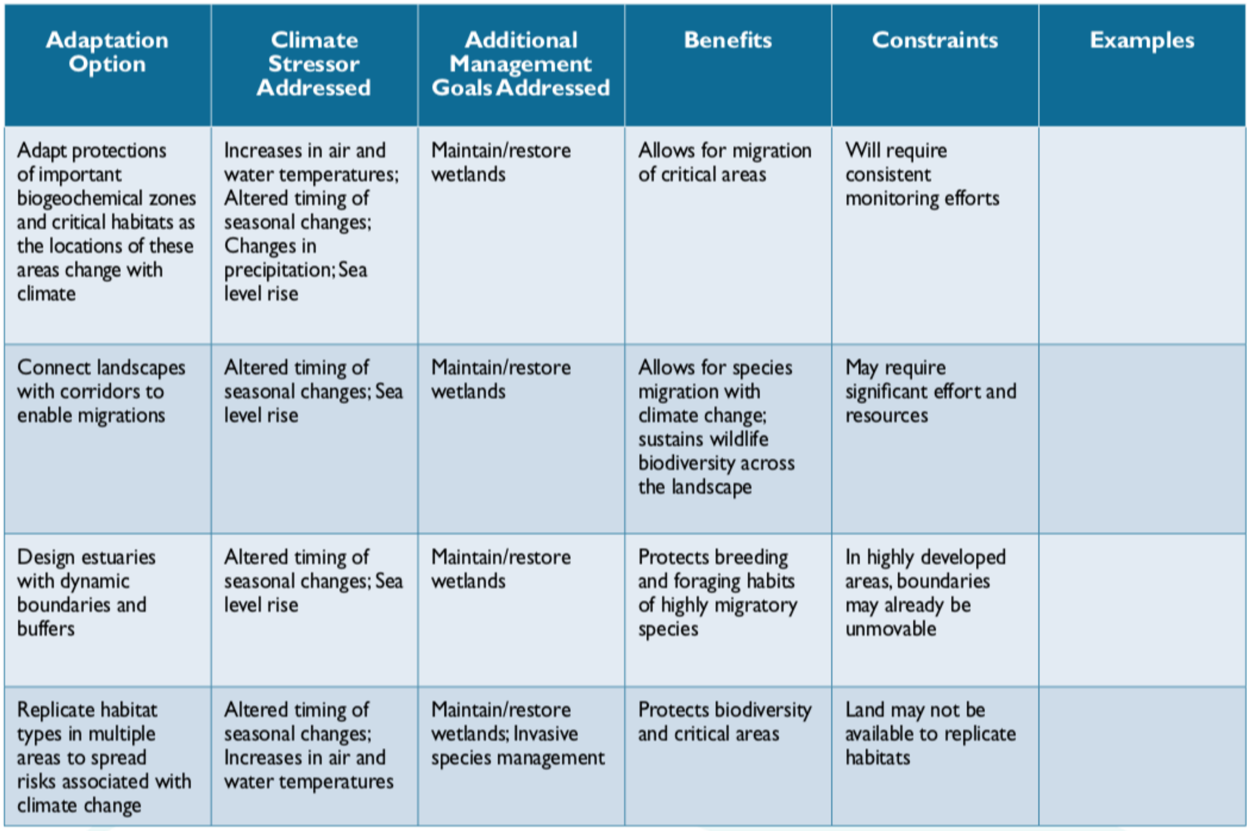


Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Strengthen rules that prevent the introductions of invasive species (e.g., enforce no discharge zones for ballast water)	Altered timing of seasonal changes; Increases in air and water temperatures	Maintain/restore wetlands; Preserve habitat for vulnerable species	Prevents difficult eradication of invasives by preventing their introductions	Difficult to regulate	Oregon[57]
Remove invasive species and restore native species	Altered timing of seasonal changes; Increases in air and water temperatures	Maintain/restore wetlands; Preserve habitat for vulnerable species	Local removals of invasives is locally viable to improve marsh characteristics that promote fish and wildlife	Difficult (if not impossible) on a larger scale	Peconic Estuary Program[58]

A.7 Adaptation Options for Preserving Habitat for Vulnerable Species

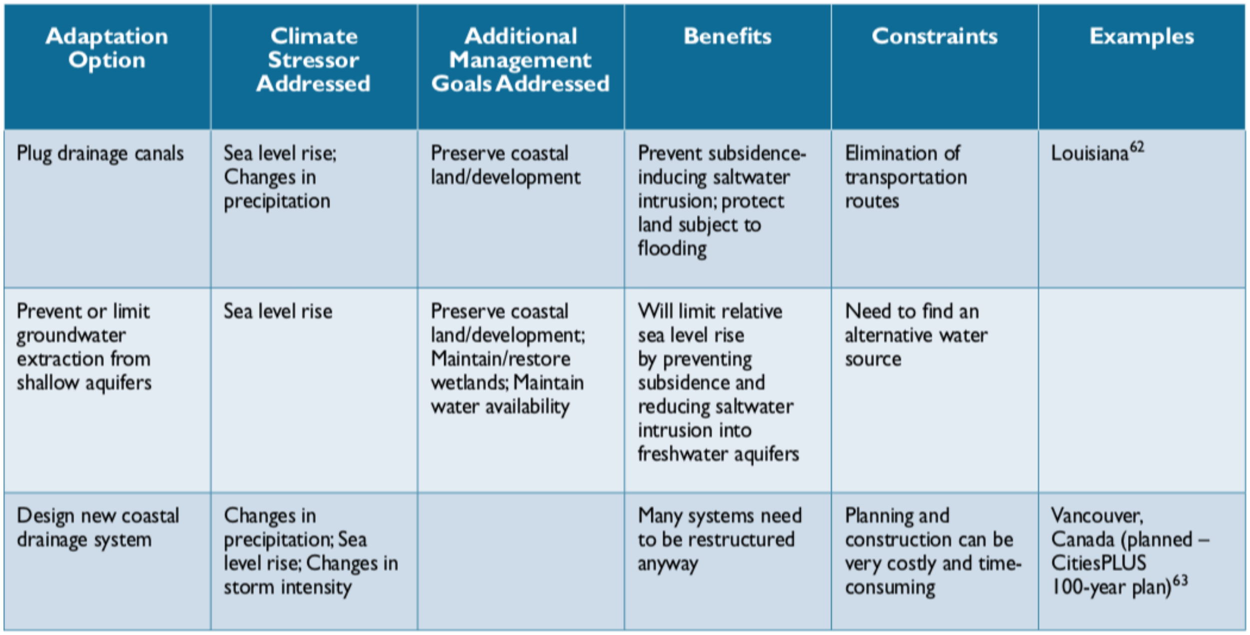


Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Retreat from, and abandonment of, coastal barriers	Sea level rise	Maintain/restore wetlands	May help protect estuaries, allowing them to return to their natural habitat	Not politically favored due to the high value of coastal property and infrastructure	
Purchase upland development rights or property rights	Changes in precipitation; Sea level rise	Maintain/restore wetlands; Maintain water quality	Protects habitats downstream	Costly; uncertainty about sea level rise means uncertainty in the amount of property purchased	San Francisco Estuary Project (planned)[59]; Massachusetts Climate Protection Plan[60]
Expand the planning horizons of land use planning to incorporate longer climate predictions	Changes in precipitation; Sea level rise	Preserve coastal land/development	Could inhibit risky development and provide protection for estuarine habitats	Land use plans rarely incorporate hard prohibitions against development close to sensitive habitats and have limited durability over time	San Francisco Bay Conservation and Development Commission (SFBCDC) has proposed recommendations[61]

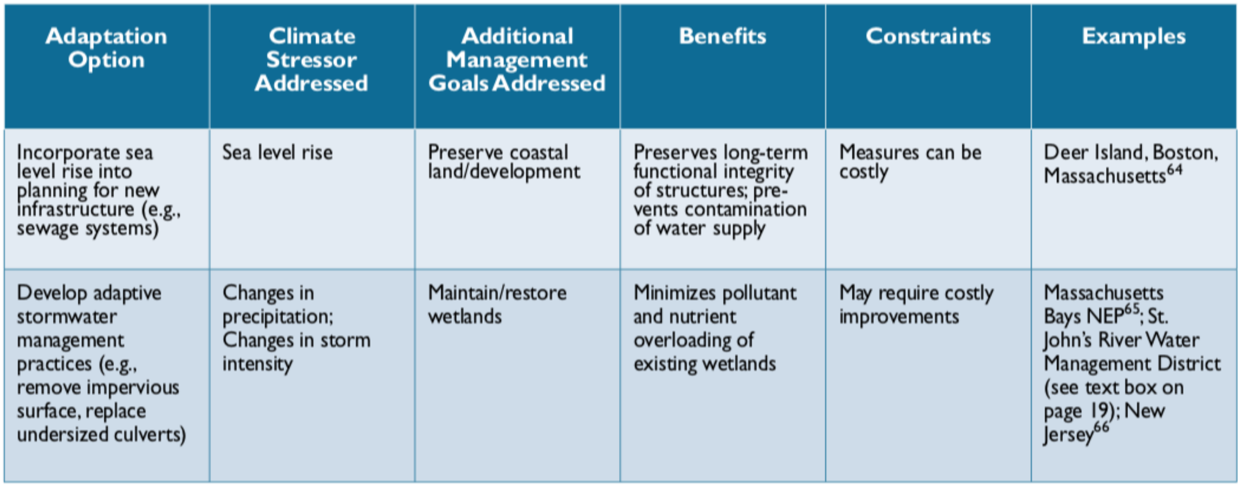


Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Adapt protections of important biogeochemical zones and critical habitats as the locations of these areas change with climate	Increases in air and water temperatures; Altered timing of seasonal changes; Changes in precipitation; Sea level rise	Maintain/restore wetlands	Allows for migration of critical areas	Will require consistent monitoring efforts	
Connect landscapes with corridors to enable migrations	Altered timing of seasonal changes; Sea level rise	Maintain/restore wetlands	Allows for species migration with climate change; sustains wildlife biodiversity across the landscape	May require significant effort and resources	
Design estuaries with dynamic boundaries and buffers	Altered timing of seasonal changes; Sea level rise	Maintain/restore wetlands	Protects breeding and foraging habits of highly migratory species	In highly developed areas, boundaries may already be unmovable	
Replicate habitat types in multiple areas to spread risks associated with climate change	Altered timing of seasonal changes; Increases in air and water temperatures	Maintain/restore wetlands; Invasive species management	Protects biodiversity and critical areas	Land may not be available to replicate habitats	

A.8 Adaptation Options for Maintaining Water Quality

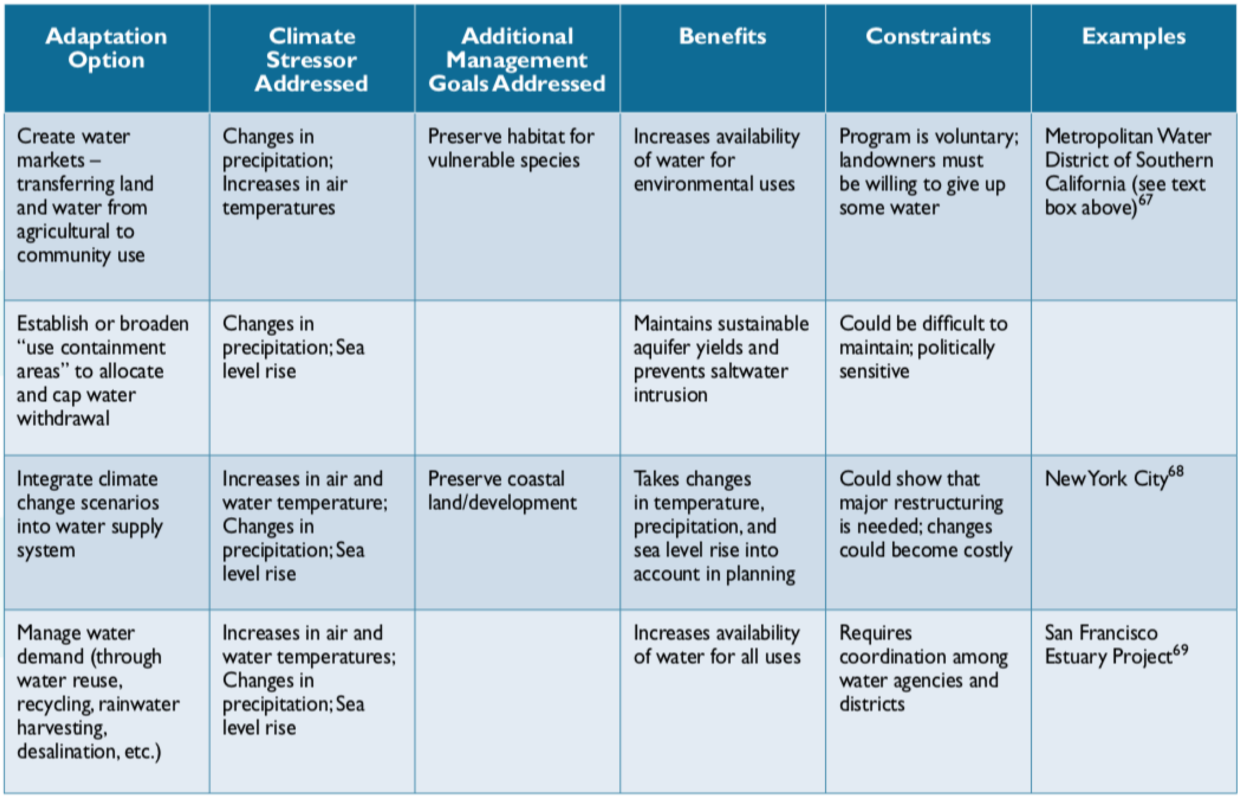


Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Plug drainage canals	Sea level rise; Changes in precipitation	Preserve coastal land/development	Prevent subsidence-inducing saltwater intrusion; protect land subject to flooding	Elimination of transportation routes	Louisiana[62]
Prevent or limit groundwater extraction from shallow aquifers	Sea level rise	Preserve coastal land/development; Maintain/restore wetlands; Maintain water availability	Will limit relative sea level rise by preventing subsidence and reducing saltwater intrusion into freshwater aquifers	Need to find an alternative water source	
Design new coastal drainage system	Changes in precipitation; Sea level rise; Changes in storm intensity		Many systems need to be restructured anyway	Planning and construction can be very costly and time-consuming	Vancouver, Canada (planned – CitiesPLUS 100-year plan)[63]



Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Incorporate sea level rise into planning for new infrastructure (e.g., sewage systems)	Sea level rise	Preserve coastal land/development	Preserves long-term functional integrity of structures; prevents contamination of water supply	Measures can be costly	Deer Island, Boston, Massachusetts[64]
Develop adaptive stormwater management practices (e.g., remove impervious surface, replace undersized culverts)	Changes in precipitation; Changes in storm intensity	Maintain/restore wetlands	Minimizes pollutant and nutrient overloading of existing wetlands	May require costly improvements	Massachusetts Bays NEP[65]; St. John's River Water Management District (see text box on page 19); New Jersey[66]

A.9 Adaptation Options for Maintaining Water Availability



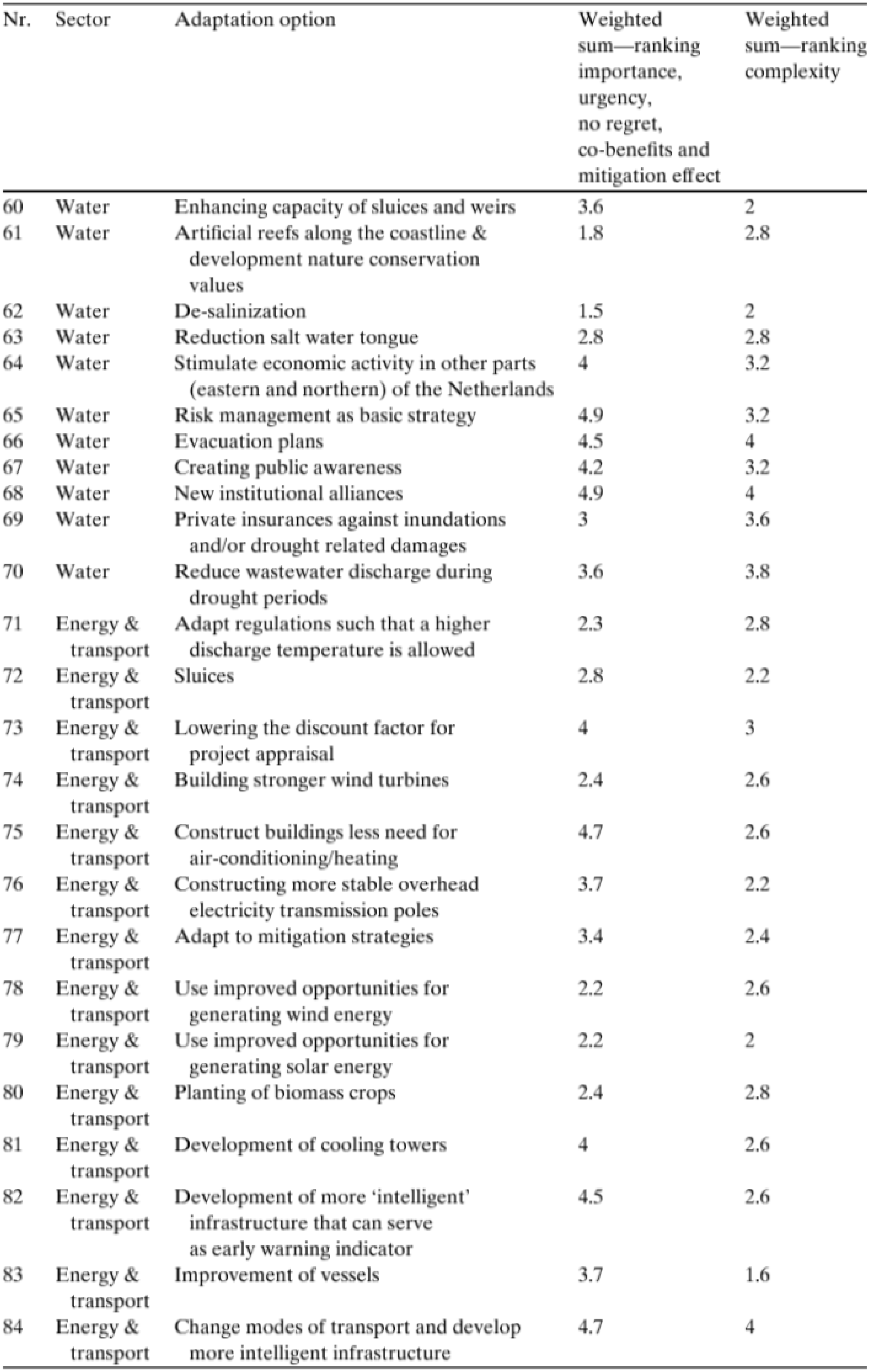
Adaptation Option	Climate Stressor Addressed	Additional Management Goals Addressed	Benefits	Constraints	Examples
Create water markets – transferring land and water from agricultural to community use	Changes in precipitation; Increases in air temperatures	Preserve habitat for vulnerable species	Increases availability of water for environmental uses	Program is voluntary; landowners must be willing to give up some water	Metropolitan Water District of Southern California (see text box above)[67]
Establish or broaden "use containment areas" to allocate and cap water withdrawal	Changes in precipitation; Sea level rise		Maintains sustainable aquifer yields and prevents saltwater intrusion	Could be difficult to maintain; politically sensitive	
Integrate climate change scenarios into water supply system	Increases in air and water temperature; Changes in precipitation; Sea level rise	Preserve coastal land/development	Takes changes in temperature, precipitation, and sea level rise into account in planning	Could show that major restructuring is needed; changes could become costly	New York City[68]
Manage water demand (through water reuse, recycling, rainwater harvesting, desalination, etc.)	Increases in air and water temperatures; Changes in precipitation; Sea level rise		Increases availability of water for all uses	Requires coordination among water agencies and districts	San Francisco Estuary Project[69]

Appendix B: Ranking of Management Strategies

B.1 Full List of Ranked Strategies

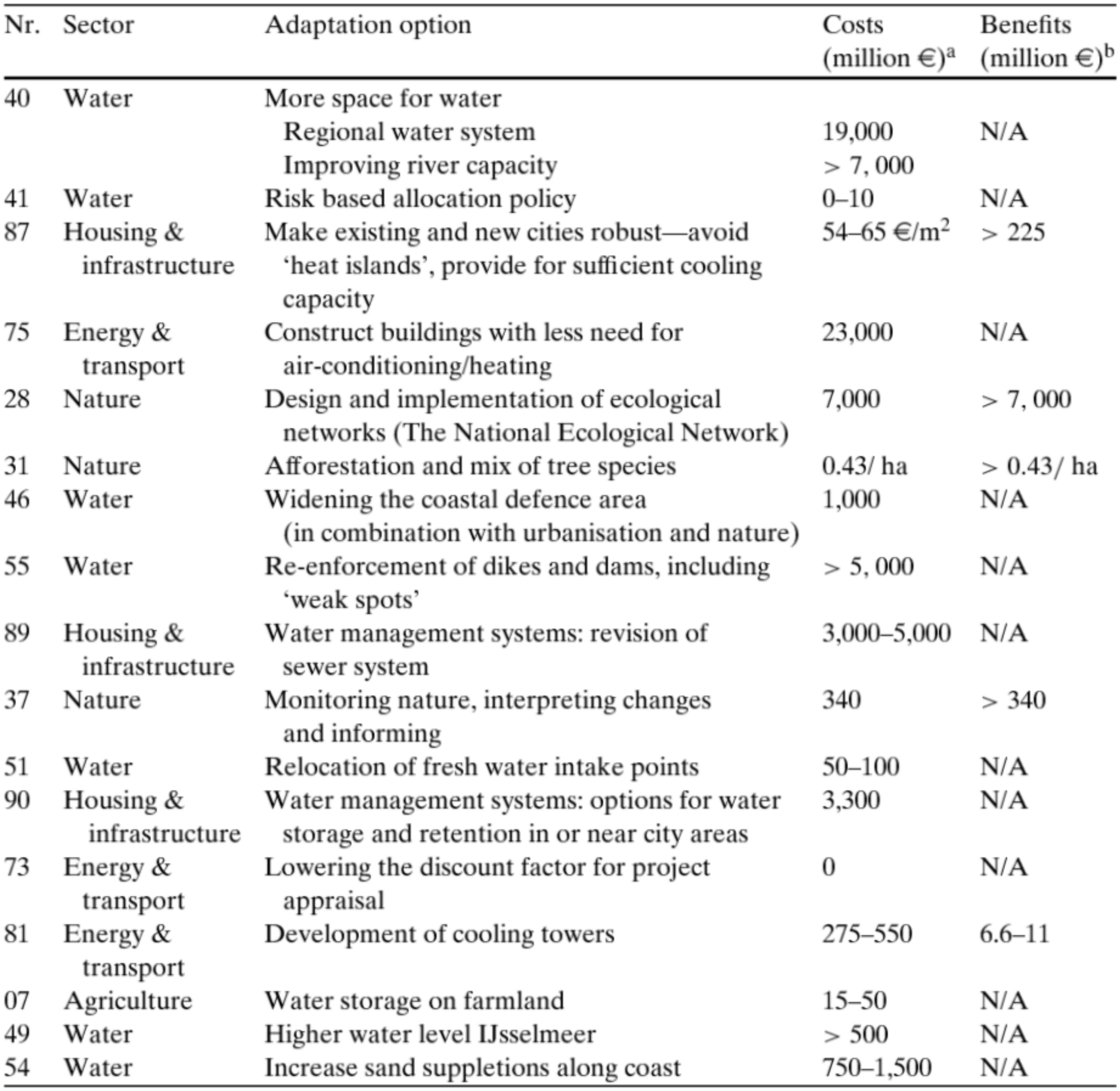
Nr.	Sector	Adaptation option	Weighted sum—ranking importance, urgency, no regret, co-benefits and mitigation effect	Weighted sum—ranking complexity
1	Agriculture	Adjusting crop rotation schemes and planting and harvesting dates	3.1	3.4
2	Agriculture	Choice of crop variety and genotype	3.5	3.4
3	Agriculture	Development and growing of crops for biomass production	2.8	3.2
4	Agriculture	Soil moisture conservation practices	3.6	2.4
5	Agriculture	Irrigation	2.9	3.2
6	Agriculture	Self sufficiency in production of roughage	1.6	2.6
7	Agriculture	Water storage on farmland	3.7	3.4
8	Agriculture	Subsoil drainage of peatlands	1.2	3.6
9	Agriculture	Insurance	3.1	3.2
10	Agriculture	Changes in farming systems	3.8	3.4
11	Agriculture	Water management and agriculture	3.4	4
12	Agriculture	Regional adaptation strategies for the fen meadow area	3	4.4
13	Agriculture	Relocation or mobilization of farms	1.6	4.2
14	Agriculture	Floating greenhouses	1.9	2.8
15	Agriculture	Land use change	3.3	4.6
16	Agriculture	Adaptation strategies to salinization of agricultural land	2.6	4
17	Agriculture	Increasing genetic and species diversity in forests	4.4	2.8
18	Agriculture	Introduction of southern provenances of tree species and drought resistant species	3.9	2.2
19	Agriculture	Limiting the import of timber	1.6	3.2
20	Agriculture	Retention of winter precipitation in forests	2.6	2.2
21	Agriculture	Acceptation of changes in species composition in forests	3.9	2.4
22	Agriculture	Adjusting fishing quota	2.6	3
23	Agriculture	Adaptation of target species and fishing techniques	2.2	2.8
24	Agriculture	Introduction of ecosystem management in fishery	4.2	3.8
25	Agriculture	Eco-labelling and certification of fish	1.5	3
26	Agriculture	Reallocation of mussel nursery plots	2.3	3.2
27	Agriculture	Aquaculture on former grassland	1.8	3.4
28	Nature	Design and implementation of ecological networks (The National Ecological Network)	4.5	3.6
29	Nature	Establishment and management of protected areas	3.4	3.4

Nr.	Sector	Adaptation option	Weighted sum—ranking importance, urgency, no regret, co-benefits and mitigation effect	Weighted sum—ranking complexity
30	Nature	Artificial translocation of plant and animal	1.6	3.6
31	Nature	Afforestation and mix of tree species	4.3	2.8
32	Nature	Adjustment of forest management	3.7	2.6
33	Nature	Implementation of effective agri-environmental schemes	3.6	4
34	Nature	Integrated nature and water management	4.9	4.2
35	Nature	Integrated coastal zone management	4.9	4.2
36	Nature	Restoration of ecosystems directly depending on water quantity and quality	3.3	3.8
37	Nature	Monitoring nature, interpreting changes and informing	4.1	2.6
38	Nature	Educational programs	4.3	2
39	Nature	Development of financing mechanisms	2.6	4
40	Water	More space for water: Regional water system Improving river capacity	4.9	4.4
41	Water	Risk based allocation policy	4.9	4.4
42	Water	Moving powerplants to coast (cooling water)	3.2	4.8
43	Water	Spatial planning of locations for powerplants (nuclear in particular)	4	4.6
44	Water	Construction of additional dikes in low-lying parts of the Netherlands	3.5	4.6
45	Water	Allow transgression of sea in wide dune areas, allow wash over of dikes	3.4	3.8
46	Water	Widening the coastal defence area (in combination with urbanisation and nature)	4.2	4.8
47	Water	Reconnecting water systems in Delta area (e.g. Volkerak Zoommeer and Oosterschelde)	3.3	4.8
48	Water	Fresh water storage to flush brackish water out during dry periods	4.3	4
49	Water	Higher water level IJsselmeer	3.6	3.4
50	Water	Maintain higher water table to prevent salt water intrusion	4.3	3.8
51	Water	Relocation of fresh water intake points	4	2.4
52	Water	Reclamation of (part of) southern North Sea	1.4	4.6
53	Water	Abandoning of the whole of low-lying Netherlands	1.3	4.8
54	Water	Increase sand suppletions along coast	3.5	2.8
55	Water	Re-enforcement of dikes and dams, including 'weak spots'	4.2	2.2
56	Water	Adapted forms of building and construction	4	3.6
57	Water	Adaptation of highways, secondary dikes to create compartments	4	4
58	Water	Protection of vital objects	3.1	2.6
59	Water	Protection of vital infrastructure	3.1	3.4



Nr.	Sector	Adaptation option	Weighted sum—ranking importance, urgency, no regret, co-benefits and mitigation effect	Weighted sum—ranking complexity
60	Water	Enhancing capacity of sluices and weirs	3.6	2
61	Water	Artificial reefs along the coastline & development nature conservation values	1.8	2.8
62	Water	De-salinization	1.5	2
63	Water	Reduction salt water tongue	2.8	2.8
64	Water	Stimulate economic activity in other parts (eastern and northern) of the Netherlands	4	3.2
65	Water	Risk management as basic strategy	4.9	3.2
66	Water	Evacuation plans	4.5	4
67	Water	Creating public awareness	4.2	3.2
68	Water	New institutional alliances	4.9	4
69	Water	Private insurances against inundations and/or drought related damages	3	3.6
70	Water	Reduce wastewater discharge during drought periods	3.6	3.8
71	Energy & transport	Adapt regulations such that a higher discharge temperature is allowed	2.3	2.8
72	Energy & transport	Sluices	2.8	2.2
73	Energy & transport	Lowering the discount factor for project appraisal	4	3
74	Energy & transport	Building stronger wind turbines	2.4	2.6
75	Energy & transport	Construct buildings less need for air-conditioning/heating	4.7	2.6
76	Energy & transport	Constructing more stable overhead electricity transmission poles	3.7	2.2
77	Energy & transport	Adapt to mitigation strategies	3.4	2.4
78	Energy & transport	Use improved opportunities for generating wind energy	2.2	2.6
79	Energy & transport	Use improved opportunities for generating solar energy	2.2	2
80	Energy & transport	Planting of biomass crops	2.4	2.8
81	Energy & transport	Development of cooling towers	4	2.6
82	Energy & transport	Development of more ‘intelligent’ infrastructure that can serve as early warning indicator	4.5	2.6
83	Energy & transport	Improvement of vessels	3.7	1.6
84	Energy & transport	Change modes of transport and develop more intelligent infrastructure	4.7	4

B.2 Cost-Benefit Analysis of Adaptation Strategies



Nr.	Sector	Adaptation option	Costs (million €)[a]	Benefits (million €)[b]
40	Water	More space for water		
		Regional water system	19,000	N/A
		Improving river capacity	> 7, 000	
41	Water	Risk based allocation policy	0–10	N/A
87	Housing & infrastructure	Make existing and new cities robust—avoid 'heat islands', provide for sufficient cooling capacity	54–65 €/m^2	> 225
75	Energy & transport	Construct buildings with less need for air-conditioning/heating	23,000	N/A
28	Nature	Design and implementation of ecological networks (The National Ecological Network)	7,000	> 7, 000
31	Nature	Afforestation and mix of tree species	0.43/ ha	> 0.43/ ha
46	Water	Widening the coastal defence area (in combination with urbanisation and nature)	1,000	N/A
55	Water	Re-enforcement of dikes and dams, including 'weak spots'	> 5, 000	N/A
89	Housing & infrastructure	Water management systems: revision of sewer system	3,000–5,000	N/A
37	Nature	Monitoring nature, interpreting changes and informing	340	> 340
51	Water	Relocation of fresh water intake points	50–100	N/A
90	Housing & infrastructure	Water management systems: options for water storage and retention in or near city areas	3,300	N/A
73	Energy & transport	Lowering the discount factor for project appraisal	0	N/A
81	Energy & transport	Development of cooling towers	275–550	6.6–11
07	Agriculture	Water storage on farmland	15–50	N/A
49	Water	Higher water level IJsselmeer	> 500	N/A
54	Water	Increase sand suppletions along coast	750–1,500	N/A

Appendix C: PLN Employee Sample Interview

PLN Team - Jacob Boles, Ari Athair, Brooke DePascale, and Dylan Parrow
Interviewee Name:

We are a team from Worcester Polytechnic Institute working with Para la Naturaleza to develop a series of recommendations to reduce the impacts of climate change in protected areas. We have developed this series of questions in order to gain insight into PLN’s current efforts towards adapting to climate change. The results of this interview will be used as we continue to assess sites, prioritize critical areas, and propose adaptation strategy recommendations.

Do you mind if we record your name for the purpose of our records?

What is your position at Para la Naturaleza? What does this role involve?

We are trying to develop a set of recommendations for adaptation to climate change in protected areas. These recommendations will be added into the next revision of PLN’s management plans. Is there information that you believe we should be looking for?

Can you direct us towards any resources?

Do you have any maps of the sites that could be useful?

What adaptation strategies are currently being implemented in the two sites?

Has a volunteer workforce been trained and recruited?

If so, how is it organized?

Most plans that we have looked at have offered information on evaluation of sites, without offering any specific recommendations for dealing with climate change impacts. Where would you suggest we find information on specific adaptation strategies; i.e. ways to adapt to coastal erosion?

What climate change models have been investigated?

Which look most promising/have been focused on?

Have any models been thrown out and if so why?

What other information have you learned since the 2010 management plans were published that will be added to future management plans for Las Cabezas de San Juan and Las Área Natural Protegida Medio Mundo y Daguao?

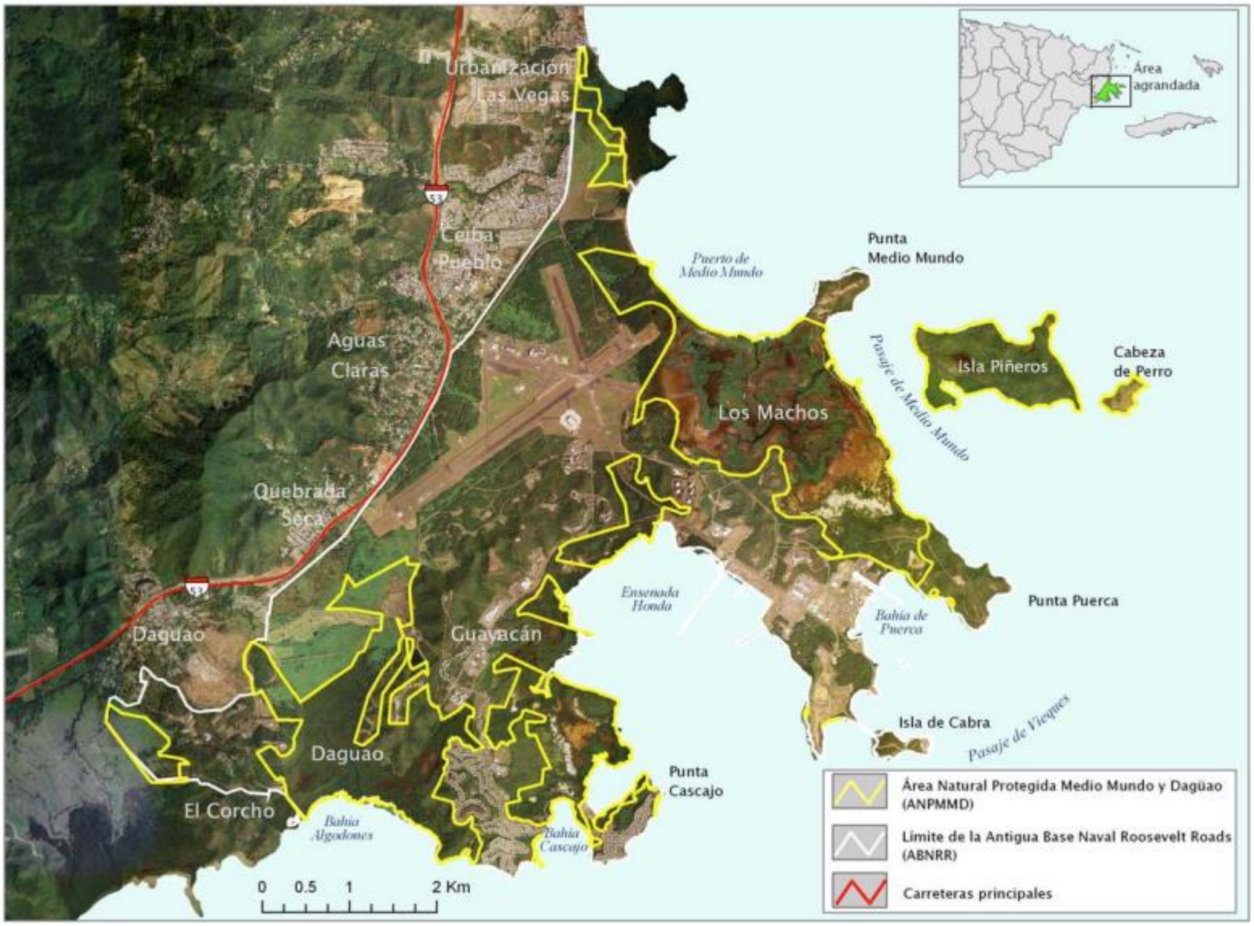
Could you locate some of the areas at each site that have been impacted by climate change using these maps?

Is there anyone else in PLN or elsewhere in Puerto Rico that is researching climate change adaptation strategies that you would recommend us to speak with?

Appendix D: Maps of Las Cabezas de San Juan and Área Natural Protegida Medio Mundo y Daguao Used During Interviews

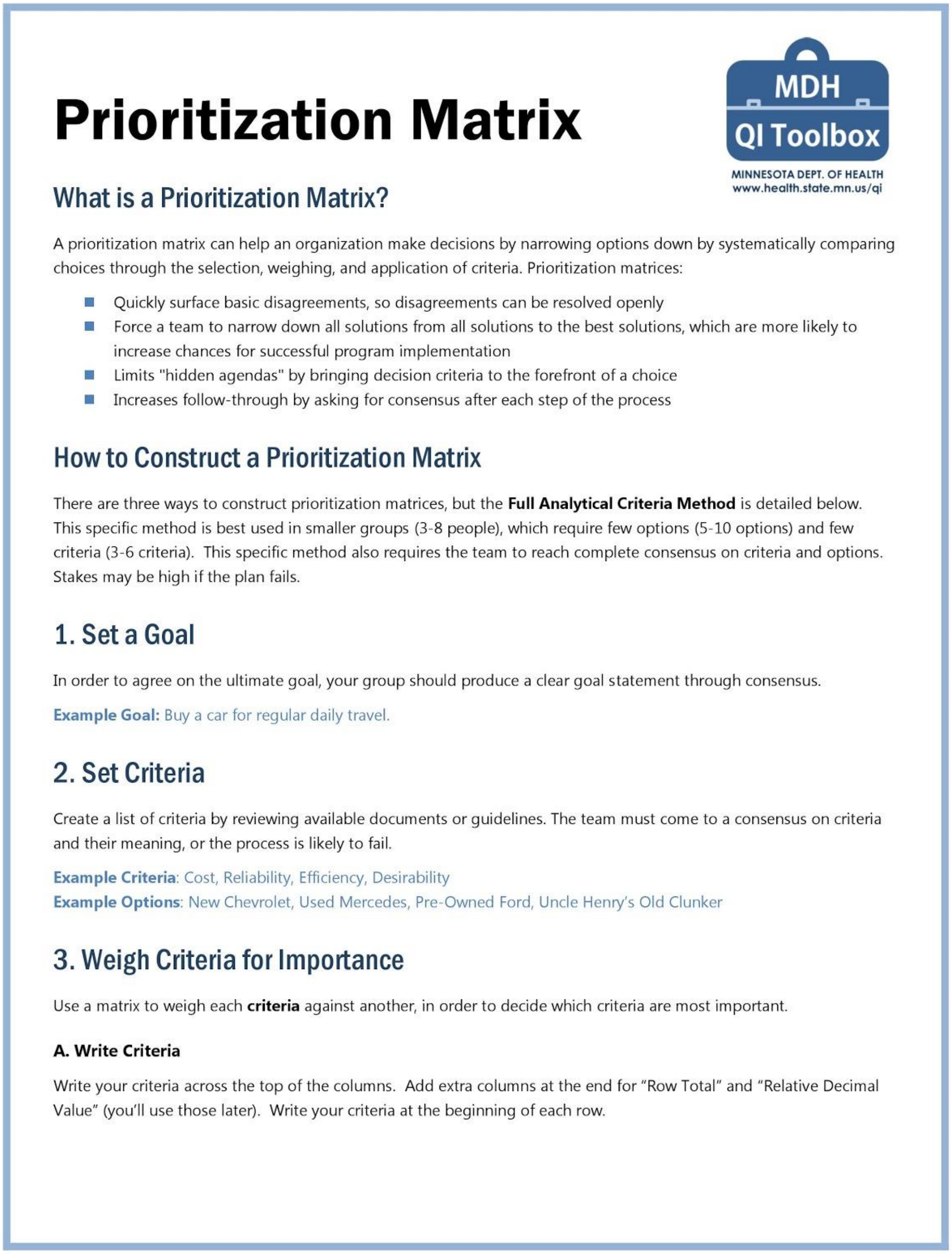
D.1 Labeled Map of Las Cabezas de San Juan

D.2 Labeled Map of Área Natural Protegida Medio Mundo y Daguao



Appendix E: Prioritization Procedure

E.1 Procedure for Prioritizing Based on Importance



Prioritization Matrix

MDH
QI Toolbox
MINNESOTA DEPT. OF HEALTH
www.health.state.mn.us/qi

What is a Prioritization Matrix?

A prioritization matrix can help an organization make decisions by narrowing options down by systematically comparing choices through the selection, weighing, and application of criteria. Prioritization matrices:

- Quickly surface basic disagreements, so disagreements can be resolved openly
- Force a team to narrow down all solutions from all solutions to the best solutions, which are more likely to increase chances for successful program implementation
- Limits "hidden agendas" by bringing decision criteria to the forefront of a choice
- Increases follow-through by asking for consensus after each step of the process

How to Construct a Prioritization Matrix

There are three ways to construct prioritization matrices, but the **Full Analytical Criteria Method** is detailed below. This specific method is best used in smaller groups (3-8 people), which require few options (5-10 options) and few criteria (3-6 criteria). This specific method also requires the team to reach complete consensus on criteria and options. Stakes may be high if the plan fails.

1. Set a Goal

In order to agree on the ultimate goal, your group should produce a clear goal statement through consensus.

Example Goal: Buy a car for regular daily travel.

2. Set Criteria

Create a list of criteria by reviewing available documents or guidelines. The team must come to a consensus on criteria and their meaning, or the process is likely to fail.

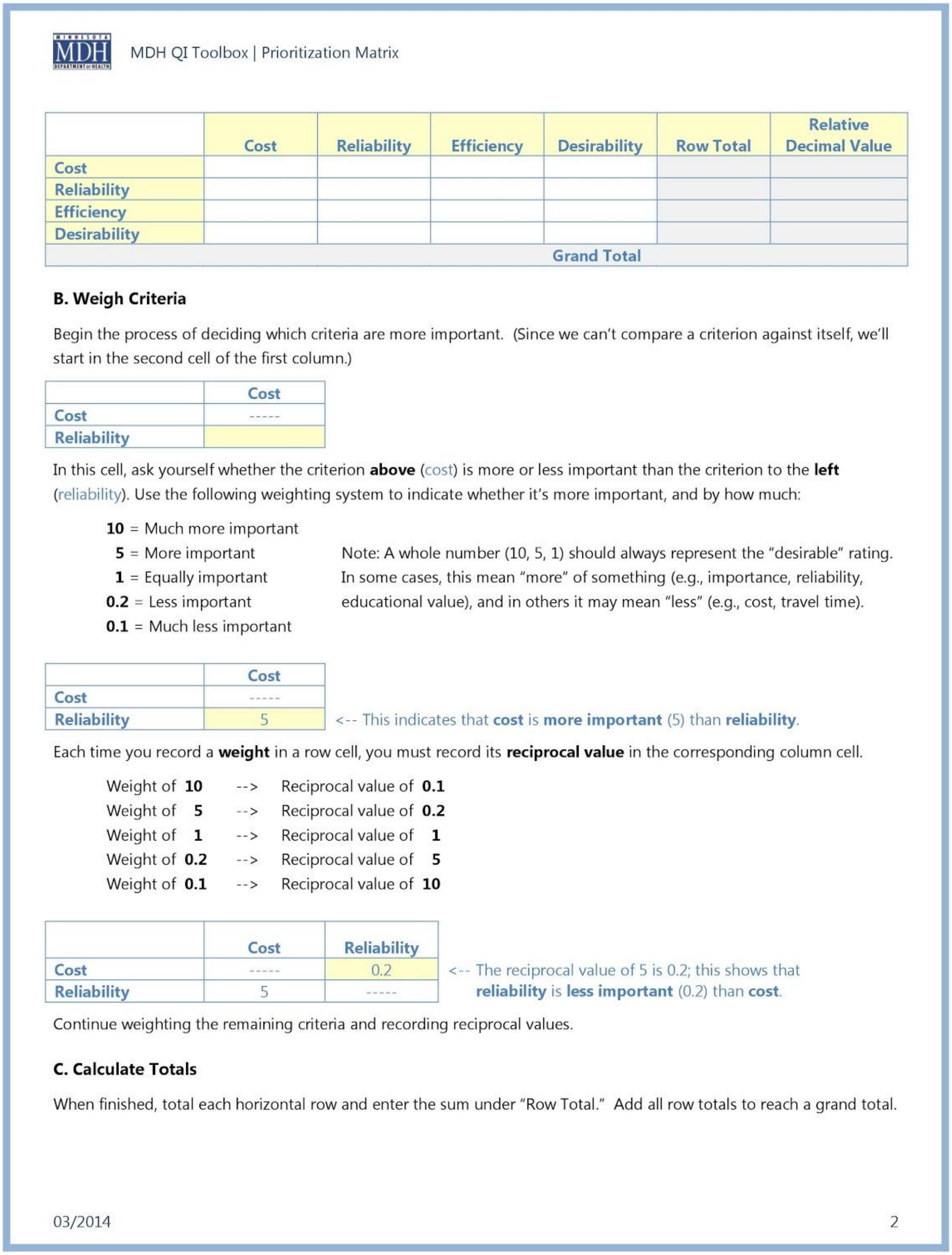
Example Criteria: Cost, Reliability, Efficiency, Desirability
Example Options: New Chevrolet, Used Mercedes, Pre-Owned Ford, Uncle Henry's Old Clunker

3. Weigh Criteria for Importance

Use a matrix to weigh each **criteria** against another, in order to decide which criteria are most important.

A. Write Criteria

Write your criteria across the top of the columns. Add extra columns at the end for "Row Total" and "Relative Decimal Value" (you'll use those later). Write your criteria at the beginning of each row.



MDH QI Toolbox | Prioritization Matrix

	Cost	Reliability	Efficiency	Desirability	Row Total	Relative Decimal Value
Cost						
Reliability						
Efficiency						
Desirability						
				Grand Total		

B. Weigh Criteria

Begin the process of deciding which criteria are more important. (Since we can't compare a criterion against itself, we'll start in the second cell of the first column.)

	Cost
Cost	-----
Reliability	

In this cell, ask yourself whether the criterion **above** (cost) is more or less important than the criterion to the **left** (reliability). Use the following weighting system to indicate whether it's more important, and by how much:

10 = Much more important
5 = More important
1 = Equally important
0.2 = Less important
0.1 = Much less important

Note: A whole number (10, 5, 1) should always represent the "desirable" rating. In some cases, this mean "more" of something (e.g., importance, reliability, educational value), and in others it may mean "less" (e.g., cost, travel time).

	Cost
Cost	-----
Reliability	5

<-- This indicates that **cost** is **more important** (5) than **reliability**.

Each time you record a **weight** in a row cell, you must record its **reciprocal value** in the corresponding column cell.

Weight of **10**	-->	Reciprocal value of **0.1**
Weight of **5**	-->	Reciprocal value of **0.2**
Weight of **1**	-->	Reciprocal value of **1**
Weight of **0.2**	-->	Reciprocal value of **5**
Weight of **0.1**	-->	Reciprocal value of **10**

	Cost	Reliability
Cost	-----	0.2
Reliability	5	-----

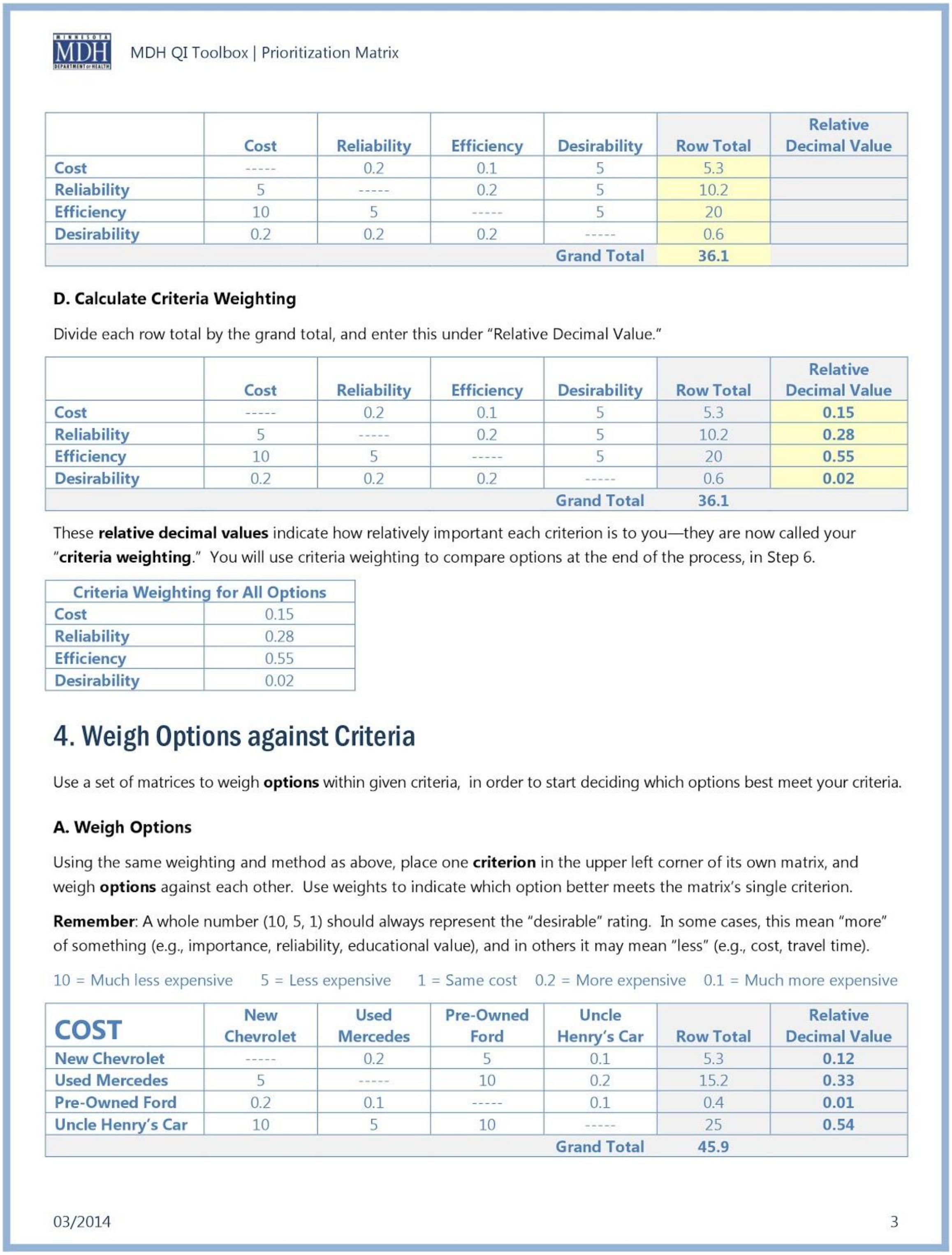
<-- The reciprocal value of 5 is 0.2; this shows that **reliability** is **less important** (0.2) than **cost**.

Continue weighting the remaining criteria and recording reciprocal values.

C. Calculate Totals

When finished, total each horizontal row and enter the sum under "Row Total." Add all row totals to reach a grand total.

03/2014 2



	Cost	Reliability	Efficiency	Desirability	Row Total	Relative Decimal Value
Cost	-----	0.2	0.1	5	5.3	
Reliability	5	-----	0.2	5	10.2	
Efficiency	10	5	-----	5	20	
Desirability	0.2	0.2	0.2	-----	0.6	
				Grand Total	**36.1**	

D. Calculate Criteria Weighting

Divide each row total by the grand total, and enter this under "Relative Decimal Value."

	Cost	Reliability	Efficiency	Desirability	Row Total	Relative Decimal Value
Cost	-----	0.2	0.1	5	5.3	**0.15**
Reliability	5	-----	0.2	5	10.2	**0.28**
Efficiency	10	5	-----	5	20	**0.55**
Desirability	0.2	0.2	0.2	-----	0.6	**0.02**
				Grand Total	**36.1**	

These **relative decimal values** indicate how relatively important each criterion is to you—they are now called your "**criteria weighting**." You will use criteria weighting to compare options at the end of the process, in Step 6.

Criteria Weighting for All Options	
Cost	0.15
Reliability	0.28
Efficiency	0.55
Desirability	0.02

4. Weigh Options against Criteria

Use a set of matrices to weigh **options** within given criteria, in order to start deciding which options best meet your criteria.

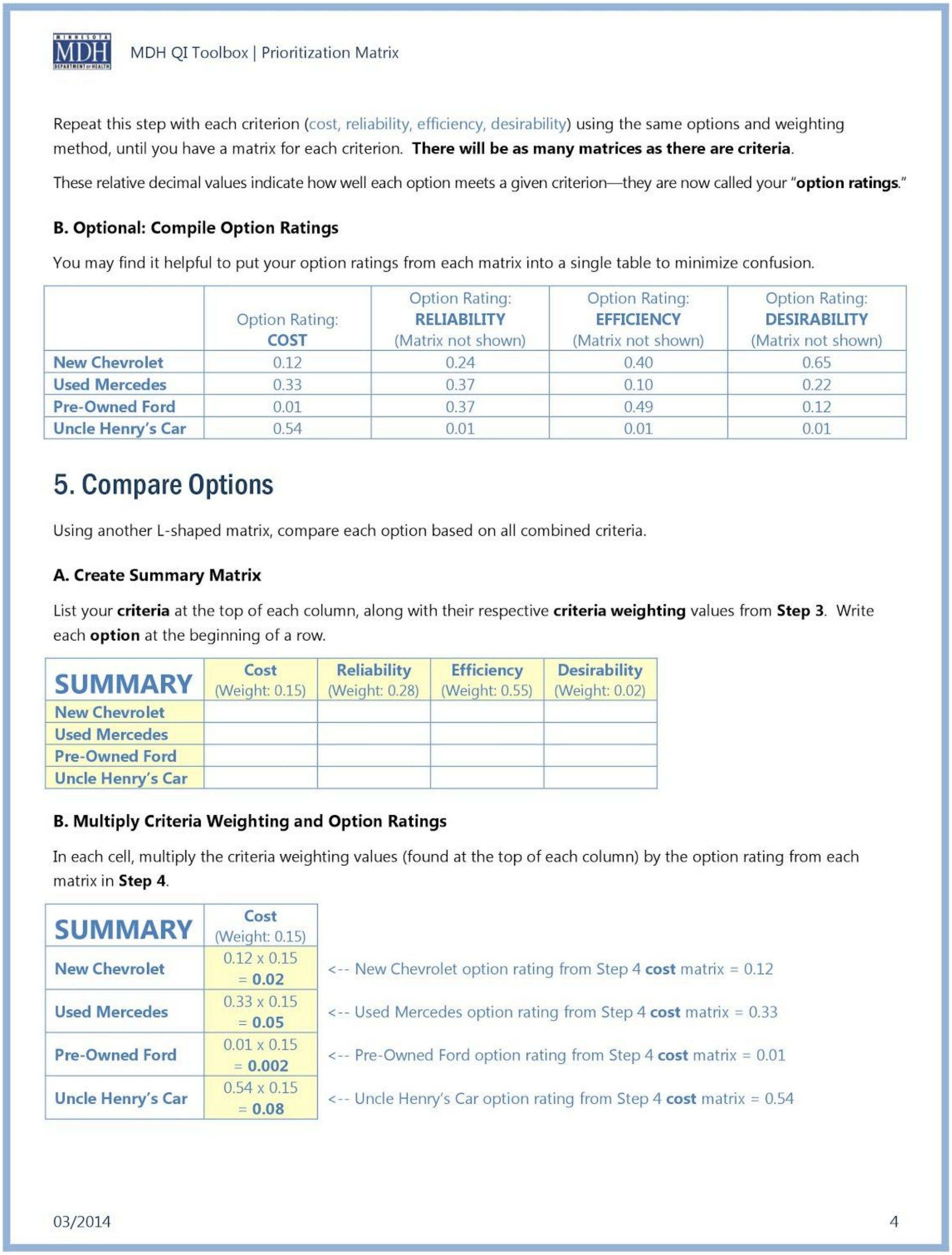
A. Weigh Options

Using the same weighting and method as above, place one **criterion** in the upper left corner of its own matrix, and weigh **options** against each other. Use weights to indicate which option better meets the matrix's single criterion.

Remember: A whole number (10, 5, 1) should always represent the "desirable" rating. In some cases, this mean "more" of something (e.g., importance, reliability, educational value), and in others it may mean "less" (e.g., cost, travel time).

10 = Much less expensive 5 = Less expensive 1 = Same cost 0.2 = More expensive 0.1 = Much more expensive

COST	New Chevrolet	Used Mercedes	Pre-Owned Ford	Uncle Henry's Car	Row Total	Relative Decimal Value
New Chevrolet	-----	0.2	5	0.1	5.3	**0.12**
Used Mercedes	5	-----	10	0.2	15.2	**0.33**
Pre-Owned Ford	0.2	0.1	-----	0.1	0.4	**0.01**
Uncle Henry's Car	10	5	10	-----	25	**0.54**
				Grand Total	**45.9**	



MDH QI Toolbox | Prioritization Matrix

Repeat this step with each criterion (cost, reliability, efficiency, desirability) using the same options and weighting method, until you have a matrix for each criterion. **There will be as many matrices as there are criteria**.

These relative decimal values indicate how well each option meets a given criterion—they are now called your "**option ratings**."

B. Optional: Compile Option Ratings

You may find it helpful to put your option ratings from each matrix into a single table to minimize confusion.

	Option Rating: **COST**	Option Rating: **RELIABILITY** (Matrix not shown)	Option Rating: **EFFICIENCY** (Matrix not shown)	Option Rating: **DESIRABILITY** (Matrix not shown)
New Chevrolet	0.12	0.24	0.40	0.65
Used Mercedes	0.33	0.37	0.10	0.22
Pre-Owned Ford	0.01	0.37	0.49	0.12
Uncle Henry's Car	0.54	0.01	0.01	0.01

5. Compare Options

Using another L-shaped matrix, compare each option based on all combined criteria.

A. Create Summary Matrix

List your **criteria** at the top of each column, along with their respective **criteria weighting** values from **Step 3**. Write each **option** at the beginning of a row.

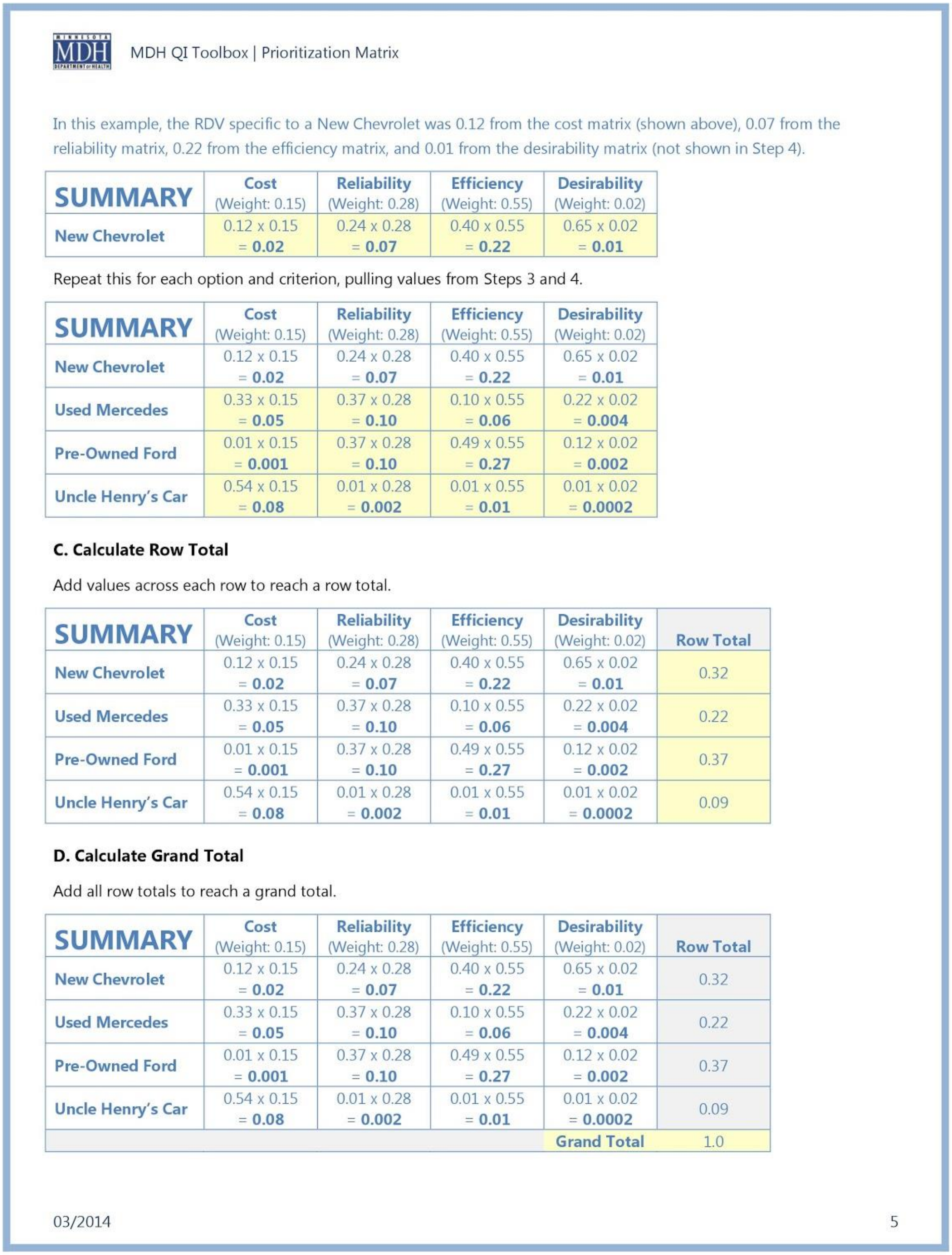
SUMMARY	**Cost** (Weight: 0.15)	**Reliability** (Weight: 0.28)	**Efficiency** (Weight: 0.55)	**Desirability** (Weight: 0.02)
New Chevrolet				
Used Mercedes				
Pre-Owned Ford				
Uncle Henry's Car				

B. Multiply Criteria Weighting and Option Ratings

In each cell, multiply the criteria weighting values (found at the top of each column) by the option rating from each matrix in **Step 4**.

SUMMARY	**Cost** (Weight: 0.15)	
New Chevrolet	0.12 x 0.15 = **0.02**	<-- New Chevrolet option rating from Step 4 **cost** matrix = 0.12
Used Mercedes	0.33 x 0.15 = **0.05**	<-- Used Mercedes option rating from Step 4 **cost** matrix = 0.33
Pre-Owned Ford	0.01 x 0.15 = **0.002**	<-- Pre-Owned Ford option rating from Step 4 **cost** matrix = 0.01
Uncle Henry's Car	0.54 x 0.15 = **0.08**	<-- Uncle Henry's Car option rating from Step 4 **cost** matrix = 0.54

03/2014 4



MDH QI Toolbox | Prioritization Matrix

In this example, the RDV specific to a New Chevrolet was 0.12 from the cost matrix (shown above), 0.07 from the reliability matrix, 0.22 from the efficiency matrix, and 0.01 from the desirability matrix (not shown in Step 4).

SUMMARY	**Cost** (Weight: 0.15)	**Reliability** (Weight: 0.28)	**Efficiency** (Weight: 0.55)	**Desirability** (Weight: 0.02)
New Chevrolet	0.12 x 0.15 = **0.02**	0.24 x 0.28 = **0.07**	0.40 x 0.55 = **0.22**	0.65 x 0.02 = **0.01**

Repeat this for each option and criterion, pulling values from Steps 3 and 4.

SUMMARY	**Cost** (Weight: 0.15)	**Reliability** (Weight: 0.28)	**Efficiency** (Weight: 0.55)	**Desirability** (Weight: 0.02)
New Chevrolet	0.12 x 0.15 = **0.02**	0.24 x 0.28 = **0.07**	0.40 x 0.55 = **0.22**	0.65 x 0.02 = **0.01**
Used Mercedes	0.33 x 0.15 = **0.05**	0.37 x 0.28 = **0.10**	0.10 x 0.55 = **0.06**	0.22 x 0.02 = **0.004**
Pre-Owned Ford	0.01 x 0.15 = **0.001**	0.37 x 0.28 = **0.10**	0.49 x 0.55 = **0.27**	0.12 x 0.02 = **0.002**
Uncle Henry's Car	0.54 x 0.15 = **0.08**	0.01 x 0.28 = **0.002**	0.01 x 0.55 = **0.01**	0.01 x 0.02 = **0.0002**

C. Calculate Row Total

Add values across each row to reach a row total.

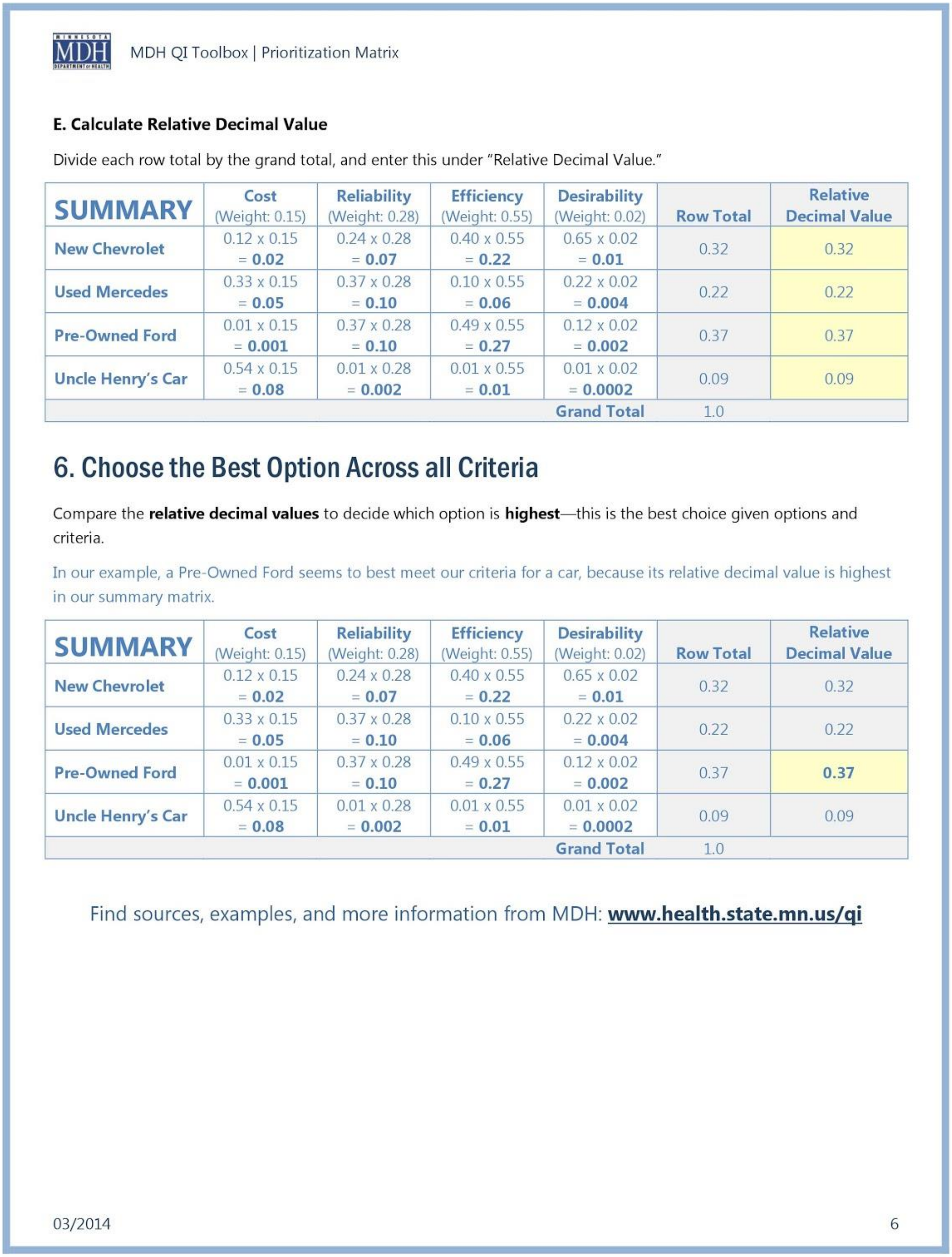
SUMMARY	**Cost** (Weight: 0.15)	**Reliability** (Weight: 0.28)	**Efficiency** (Weight: 0.55)	**Desirability** (Weight: 0.02)	**Row Total**
New Chevrolet	0.12 x 0.15 = **0.02**	0.24 x 0.28 = **0.07**	0.40 x 0.55 = **0.22**	0.65 x 0.02 = **0.01**	0.32
Used Mercedes	0.33 x 0.15 = **0.05**	0.37 x 0.28 = **0.10**	0.10 x 0.55 = **0.06**	0.22 x 0.02 = **0.004**	0.22
Pre-Owned Ford	0.01 x 0.15 = **0.001**	0.37 x 0.28 = **0.10**	0.49 x 0.55 = **0.27**	0.12 x 0.02 = **0.002**	0.37
Uncle Henry's Car	0.54 x 0.15 = **0.08**	0.01 x 0.28 = **0.002**	0.01 x 0.55 = **0.01**	0.01 x 0.02 = **0.0002**	0.09

D. Calculate Grand Total

Add all row totals to reach a grand total.

SUMMARY	**Cost** (Weight: 0.15)	**Reliability** (Weight: 0.28)	**Efficiency** (Weight: 0.55)	**Desirability** (Weight: 0.02)	**Row Total**
New Chevrolet	0.12 x 0.15 = **0.02**	0.24 x 0.28 = **0.07**	0.40 x 0.55 = **0.22**	0.65 x 0.02 = **0.01**	0.32
Used Mercedes	0.33 x 0.15 = **0.05**	0.37 x 0.28 = **0.10**	0.10 x 0.55 = **0.06**	0.22 x 0.02 = **0.004**	0.22
Pre-Owned Ford	0.01 x 0.15 = **0.001**	0.37 x 0.28 = **0.10**	0.49 x 0.55 = **0.27**	0.12 x 0.02 = **0.002**	0.37
Uncle Henry's Car	0.54 x 0.15 = **0.08**	0.01 x 0.28 = **0.002**	0.01 x 0.55 = **0.01**	0.01 x 0.02 = **0.0002**	0.09
				Grand Total	1.0

03/2014 5



MDH QI Toolbox | Prioritization Matrix

E. Calculate Relative Decimal Value

Divide each row total by the grand total, and enter this under "Relative Decimal Value."

SUMMARY	Cost (Weight: 0.15)	Reliability (Weight: 0.28)	Efficiency (Weight: 0.55)	Desirability (Weight: 0.02)	Row Total	Relative Decimal Value
New Chevrolet	0.12 x 0.15 = **0.02**	0.24 x 0.28 = **0.07**	0.40 x 0.55 = **0.22**	0.65 x 0.02 = **0.01**	0.32	0.32
Used Mercedes	0.33 x 0.15 = **0.05**	0.37 x 0.28 = **0.10**	0.10 x 0.55 = **0.06**	0.22 x 0.02 = **0.004**	0.22	0.22
Pre-Owned Ford	0.01 x 0.15 = **0.001**	0.37 x 0.28 = **0.10**	0.49 x 0.55 = **0.27**	0.12 x 0.02 = **0.002**	0.37	0.37
Uncle Henry's Car	0.54 x 0.15 = **0.08**	0.01 x 0.28 = **0.002**	0.01 x 0.55 = **0.01**	0.01 x 0.02 = **0.0002**	0.09	0.09
				Grand Total	1.0	

6. Choose the Best Option Across all Criteria

Compare the **relative decimal values** to decide which option is **highest**—this is the best choice given options and criteria.

In our example, a Pre-Owned Ford seems to best meet our criteria for a car, because its relative decimal value is highest in our summary matrix.

SUMMARY	Cost (Weight: 0.15)	Reliability (Weight: 0.28)	Efficiency (Weight: 0.55)	Desirability (Weight: 0.02)	Row Total	Relative Decimal Value
New Chevrolet	0.12 x 0.15 = **0.02**	0.24 x 0.28 = **0.07**	0.40 x 0.55 = **0.22**	0.65 x 0.02 = **0.01**	0.32	0.32
Used Mercedes	0.33 x 0.15 = **0.05**	0.37 x 0.28 = **0.10**	0.10 x 0.55 = **0.06**	0.22 x 0.02 = **0.004**	0.22	0.22
Pre-Owned Ford	0.01 x 0.15 = **0.001**	0.37 x 0.28 = **0.10**	0.49 x 0.55 = **0.27**	0.12 x 0.02 = **0.002**	0.37	**0.37**
Uncle Henry's Car	0.54 x 0.15 = **0.08**	0.01 x 0.28 = **0.002**	0.01 x 0.55 = **0.01**	0.01 x 0.02 = **0.0002**	0.09	0.09
				Grand Total	1.0	

Find sources, examples, and more information from MDH: **www.health.state.mn.us/qi**

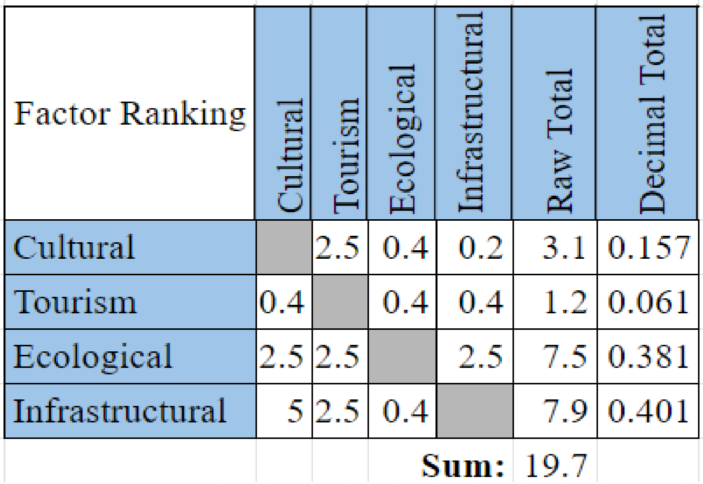
03/2014 6

E.2 Point System Procedure for Prioritizing Based on Vulnerability

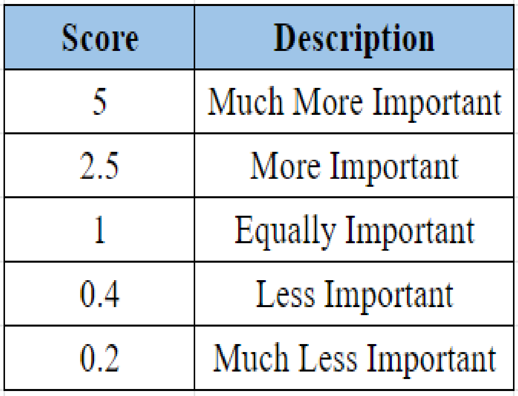
Points for Sea Level Rise	
4	Portions of this area will be inundated after 1 foot of SLR such that it would impact the usage/function of the area.
3	Portions of this area will be inundated after 3 feet of SLR such that it would impact the usage/function of the area.
2	Portions of this area will be inundated after 6 feet of SLR such that it would impact the usage/function of the area.
1	Portions of this area have the potential to be inundated by SLR greater than 6 feet such that it would impact the usage/function of the area.
0	This area’s location indicates there is no reasonable possibility that it will be inundated in the foreseeable future.
Points for Coastal Erosion	
2	Area is already showing visible signs of erosion.
1	This area’s location within 10 meters of the coastline could put the area at risk of erosion during extreme weather events or once SLR progresses.
0	This area’s location indicates that there is no reasonable possibility that it will be subject to coastal erosion in the foreseeable future.
Points for FEMA Floodplain Classification (Flood Zones, n.d.)	
2	AO - River or stream flood hazard area with a 1% or greater annual chance of flooding usually in the form of sheet flow in the one foot to three-foot range.
2	VE - Area along the coast susceptible an annual flood risk of 1% plus additional risks caused by the speed of the waves due to the effects of the storm.
1	AE - Areas susceptible to an annual flood risk of 1%.
0	No floodplain designation in this area.
Points for Susceptibility to Extreme Weather Events	
1	This area’s immediate proximity to coast or open exposure make it particularly susceptible to the effects of extreme weather events such as hurricanes.
0	This area is located away from the coast or is protected by natural or manmade features such that it has a standard level of risk to damage from extreme weather events such as hurricanes.

Appendix F: Prioritization Results

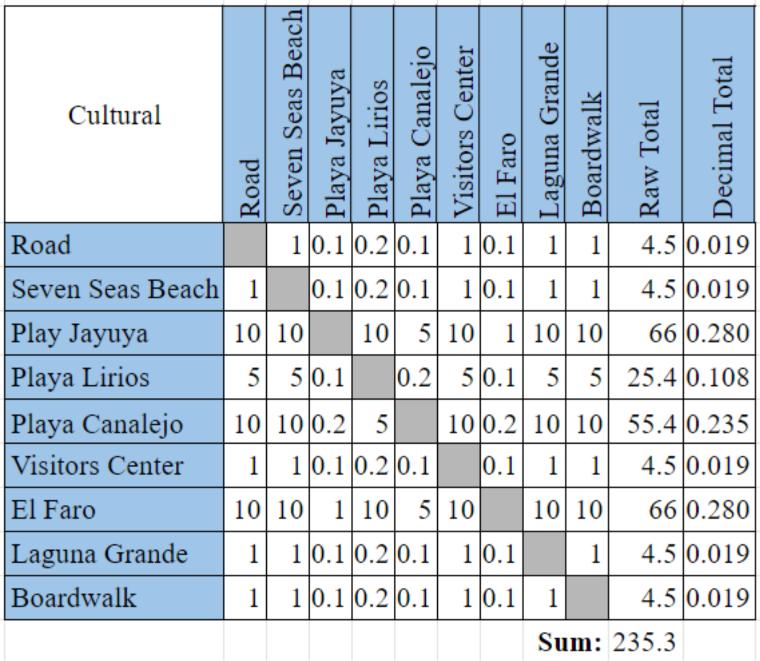
F.1 Raw Data from Importance Based Prioritization at Las Cabezas de San Juan Nature Reserve



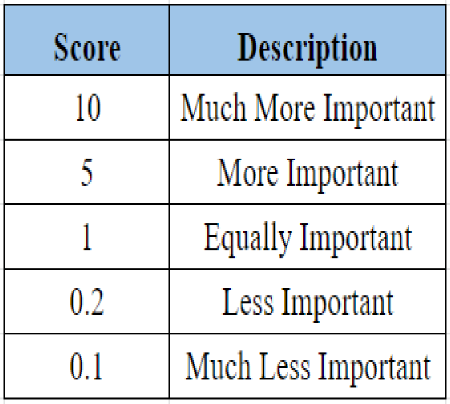
Factor Ranking	Cultural	Tourism	Ecological	Infrastructural	Raw Total	Decimal Total
Cultural		2.5	0.4	0.2	3.1	0.157
Tourism	0.4		0.4	0.4	1.2	0.061
Ecological	2.5	2.5		2.5	7.5	0.381
Infrastructural	5	2.5	0.4		7.9	0.401
				Sum:	19.7	



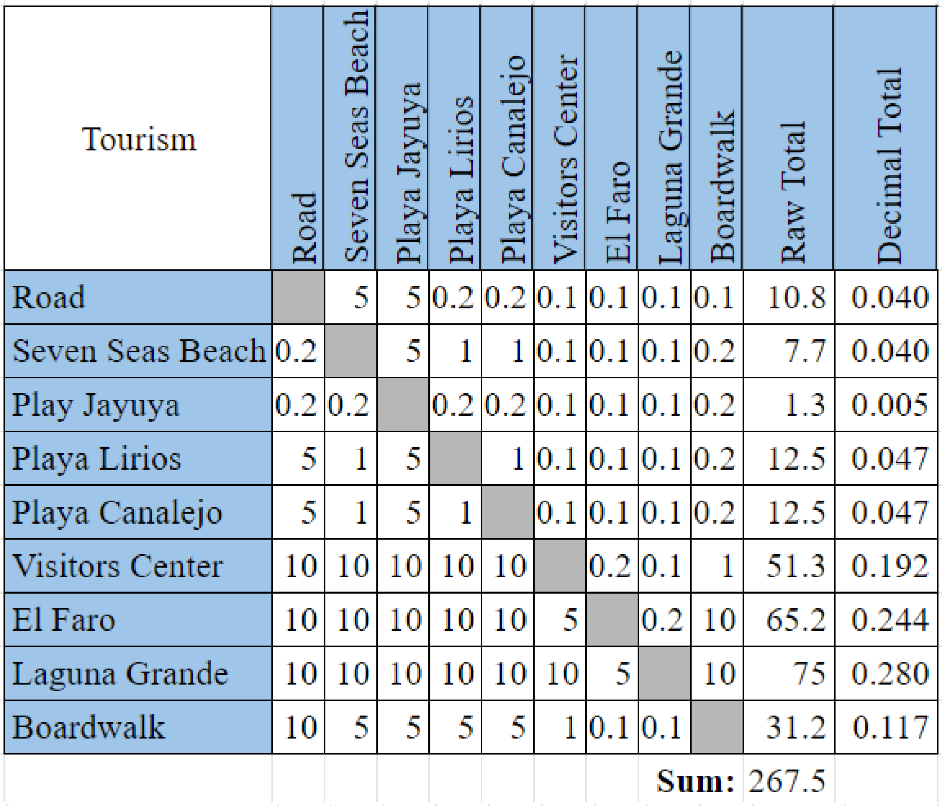
Score	Description
5	Much More Important
2.5	More Important
1	Equally Important
0.4	Less Important
0.2	Much Less Important



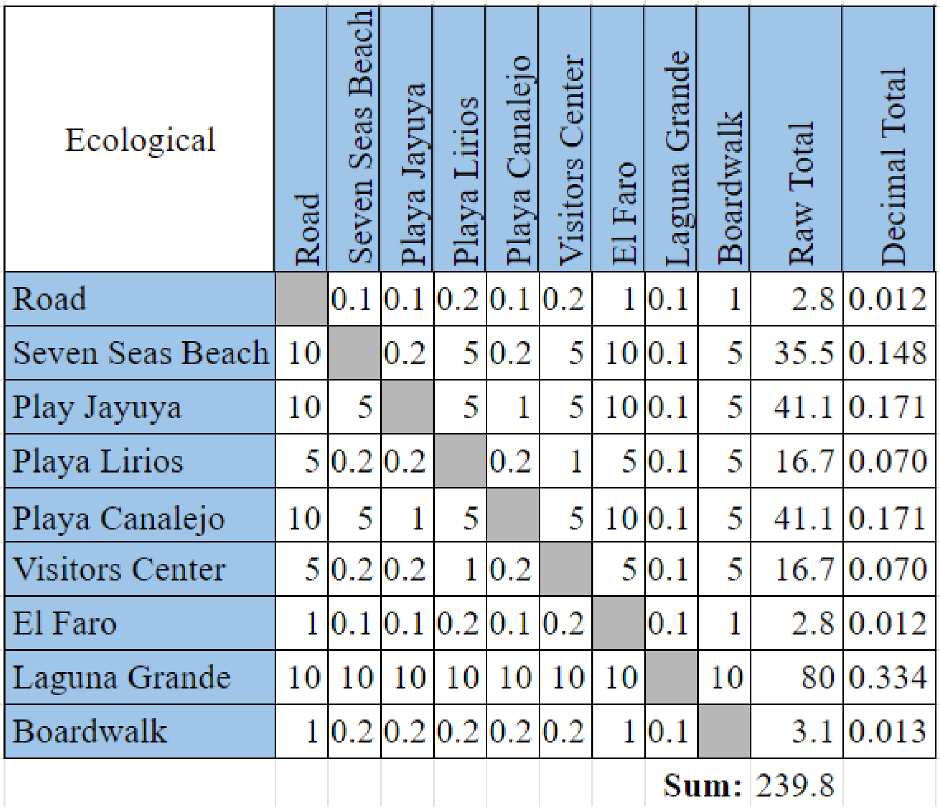
Cultural	Road	Seven Seas Beach	Playa Jayuya	Playa Lirios	Playa Canalejo	Visitors Center	El Faro	Laguna Grande	Boardwalk	Raw Total	Decimal Total
Road		1	0.1	0.2	0.1	1	0.1	1	1	4.5	0.019
Seven Seas Beach	1		0.1	0.2	0.1	1	0.1	1	1	4.5	0.019
Play Jayuya	10	10		10	5	10	1	10	10	66	0.280
Playa Lirios	5	5	0.1		0.2	5	0.1	5	5	25.4	0.108
Playa Canalejo	10	10	0.2	5		10	0.2	10	10	55.4	0.235
Visitors Center	1	1	0.1	0.2	0.1		0.1	1	1	4.5	0.019
El Faro	10	10	1	10	5	10		10	10	66	0.280
Laguna Grande	1	1	0.1	0.2	0.1	1	0.1		1	4.5	0.019
Boardwalk	1	1	0.1	0.2	0.1	1	0.1	1		4.5	0.019
									Sum:	235.3	



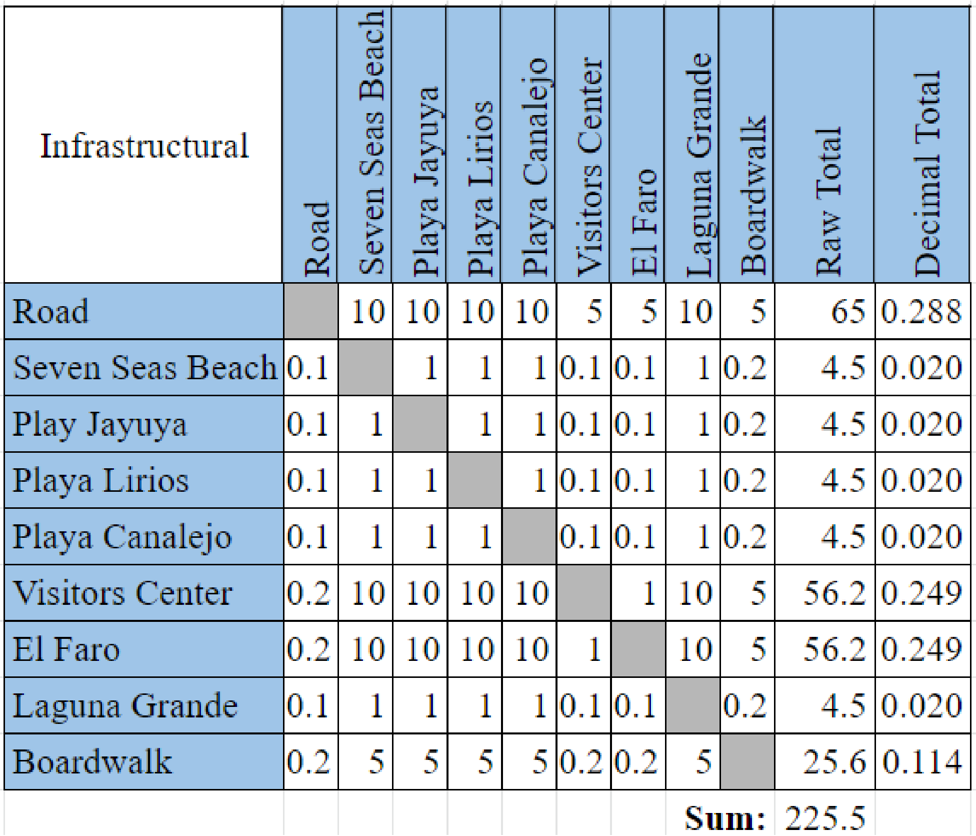
Score	Description
10	Much More Important
5	More Important
1	Equally Important
0.2	Less Important
0.1	Much Less Important



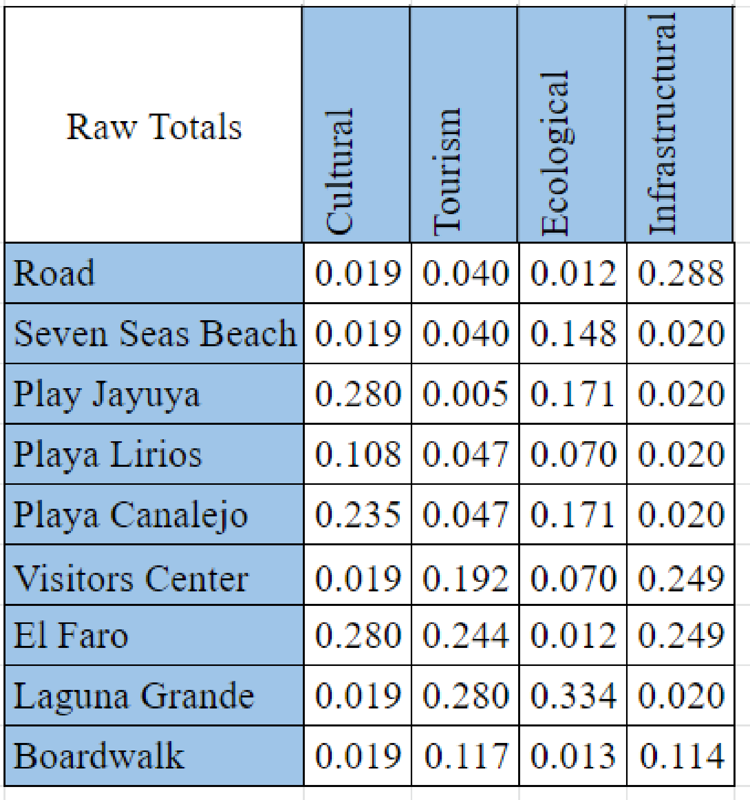
Tourism	Road	Seven Seas Beach	Playa Jayuya	Playa Lirios	Playa Canalejo	Visitors Center	El Faro	Laguna Grande	Boardwalk	Raw Total	Decimal Total
Road		5	5	0.2	0.2	0.1	0.1	0.1	0.1	10.8	0.040
Seven Seas Beach	0.2		5	1	1	0.1	0.1	0.1	0.2	7.7	0.040
Play Jayuya	0.2	0.2		0.2	0.2	0.1	0.1	0.1	0.2	1.3	0.005
Playa Lirios	5	1	5		1	0.1	0.1	0.1	0.2	12.5	0.047
Playa Canalejo	5	1	5	1		0.1	0.1	0.1	0.2	12.5	0.047
Visitors Center	10	10	10	10	10		0.2	0.1	1	51.3	0.192
El Faro	10	10	10	10	10	5		0.2	10	65.2	0.244
Laguna Grande	10	10	10	10	10	10	5		10	75	0.280
Boardwalk	10	5	5	5	5	1	0.1	0.1		31.2	0.117
									Sum:	267.5	



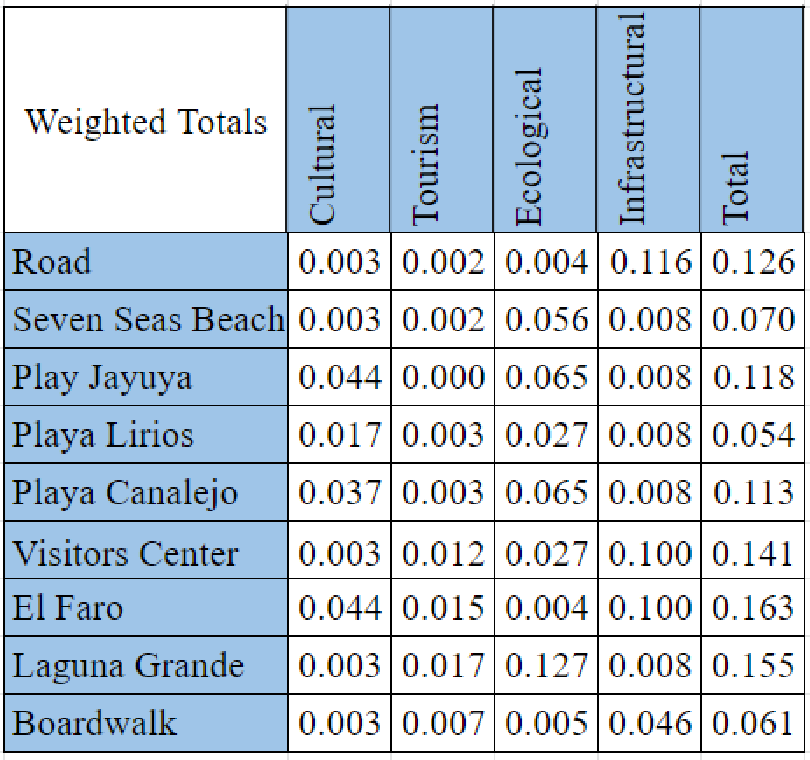
Ecological	Road	Seven Seas Beach	Playa Jayuya	Playa Lirios	Playa Canalejo	Visitors Center	El Faro	Laguna Grande	Boardwalk	Raw Total	Decimal Total
Road		0.1	0.1	0.2	0.1	0.2	1	0.1	1	2.8	0.012
Seven Seas Beach	10		0.2	5	0.2	5	10	0.1	5	35.5	0.148
Play Jayuya	10	5		5	1	5	10	0.1	5	41.1	0.171
Playa Lirios	5	0.2	0.2		0.2	1	5	0.1	5	16.7	0.070
Playa Canalejo	10	5	1	5		5	10	0.1	5	41.1	0.171
Visitors Center	5	0.2	0.2	1	0.2		5	0.1	5	16.7	0.070
El Faro	1	0.1	0.1	0.2	0.1	0.2		0.1	1	2.8	0.012
Laguna Grande	10	10	10	10	10	10	10		10	80	0.334
Boardwalk	1	0.2	0.2	0.2	0.2	0.2	1	0.1		3.1	0.013
									Sum:	239.8	



Infrastructural	Road	Seven Seas Beach	Playa Jayuya	Playa Lirios	Playa Canalejo	Visitors Center	El Faro	Laguna Grande	Boardwalk	Raw Total	Decimal Total
Road		10	10	10	10	5	5	10	5	65	0.288
Seven Seas Beach	0.1		1	1	1	0.1	0.1	1	0.2	4.5	0.020
Play Jayuya	0.1	1		1	1	0.1	0.1	1	0.2	4.5	0.020
Playa Lirios	0.1	1	1		1	0.1	0.1	1	0.2	4.5	0.020
Playa Canalejo	0.1	1	1	1		0.1	0.1	1	0.2	4.5	0.020
Visitors Center	0.2	10	10	10	10		1	10	5	56.2	0.249
El Faro	0.2	10	10	10	10	1		10	5	56.2	0.249
Laguna Grande	0.1	1	1	1	1	0.1	0.1		0.2	4.5	0.020
Boardwalk	0.2	5	5	5	5	0.2	0.2	5		25.6	0.114
									Sum:	225.5	

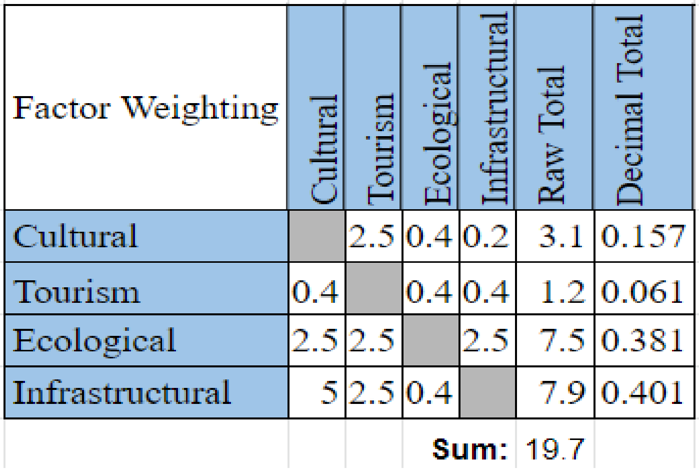


Raw Totals	Cultural	Tourism	Ecological	Infrastructural
Road	0.019	0.040	0.012	0.288
Seven Seas Beach	0.019	0.040	0.148	0.020
Play Jayuya	0.280	0.005	0.171	0.020
Playa Lirios	0.108	0.047	0.070	0.020
Playa Canalejo	0.235	0.047	0.171	0.020
Visitors Center	0.019	0.192	0.070	0.249
El Faro	0.280	0.244	0.012	0.249
Laguna Grande	0.019	0.280	0.334	0.020
Boardwalk	0.019	0.117	0.013	0.114

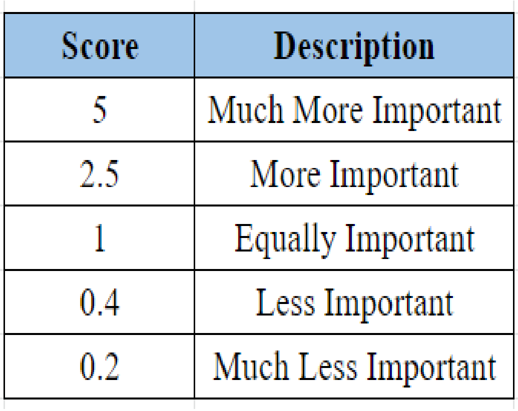


Weighted Totals	Cultural	Tourism	Ecological	Infrastructural	Total
Road	0.003	0.002	0.004	0.116	0.126
Seven Seas Beach	0.003	0.002	0.056	0.008	0.070
Play Jayuya	0.044	0.000	0.065	0.008	0.118
Playa Lirios	0.017	0.003	0.027	0.008	0.054
Playa Canalejo	0.037	0.003	0.065	0.008	0.113
Visitors Center	0.003	0.012	0.027	0.100	0.141
El Faro	0.044	0.015	0.004	0.100	0.163
Laguna Grande	0.003	0.017	0.127	0.008	0.155
Boardwalk	0.003	0.007	0.005	0.046	0.061

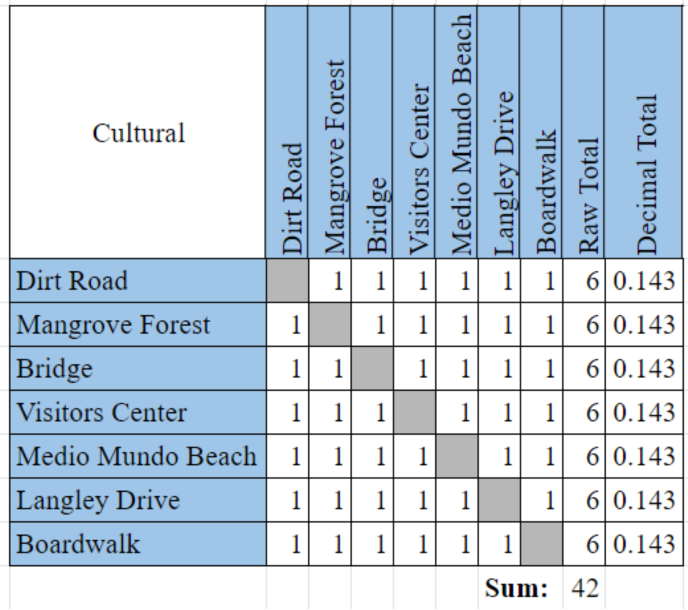
F.2 Raw Data from Importance Based Prioritization at Área Natural Protegida Medio Mundo y Daguao



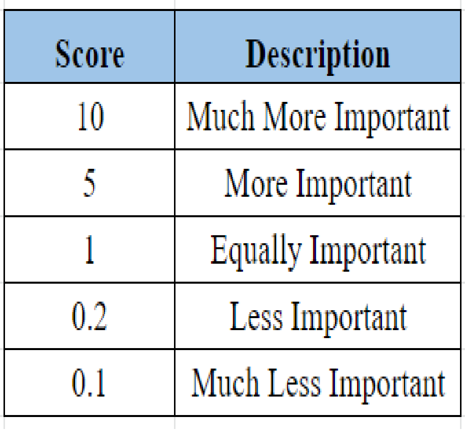
Factor Weighting	Cultural	Tourism	Ecological	Infrastructural	Raw Total	Decimal Total
Cultural		2.5	0.4	0.2	3.1	0.157
Tourism	0.4		0.4	0.4	1.2	0.061
Ecological	2.5	2.5		2.5	7.5	0.381
Infrastructural	5	2.5	0.4		7.9	0.401
				Sum:	19.7	



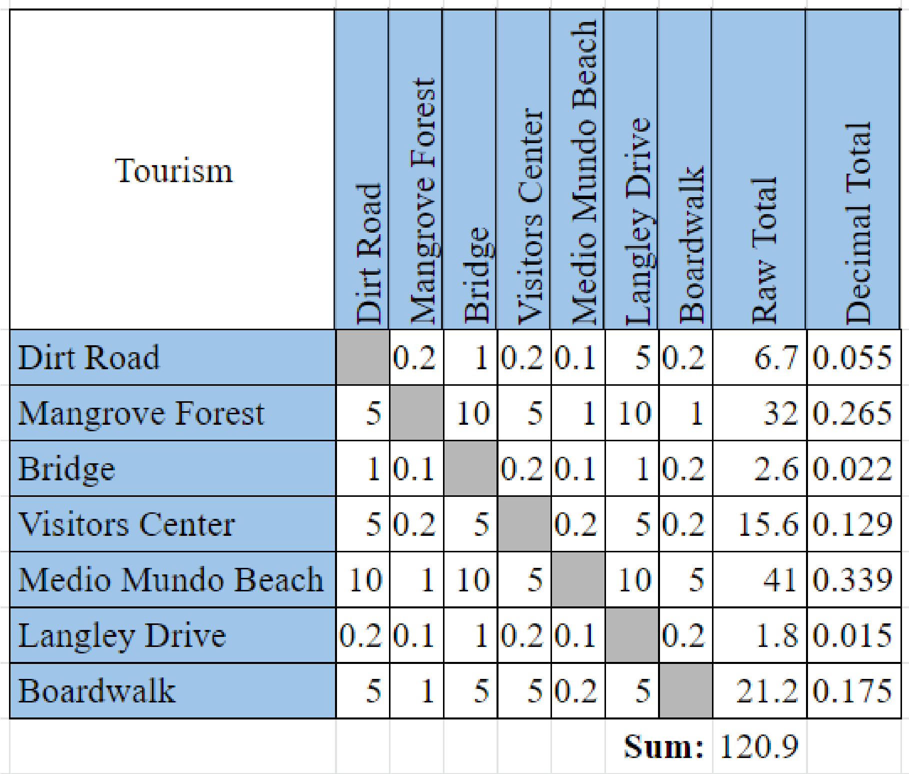
Score	Description
5	Much More Important
2.5	More Important
1	Equally Important
0.4	Less Important
0.2	Much Less Important



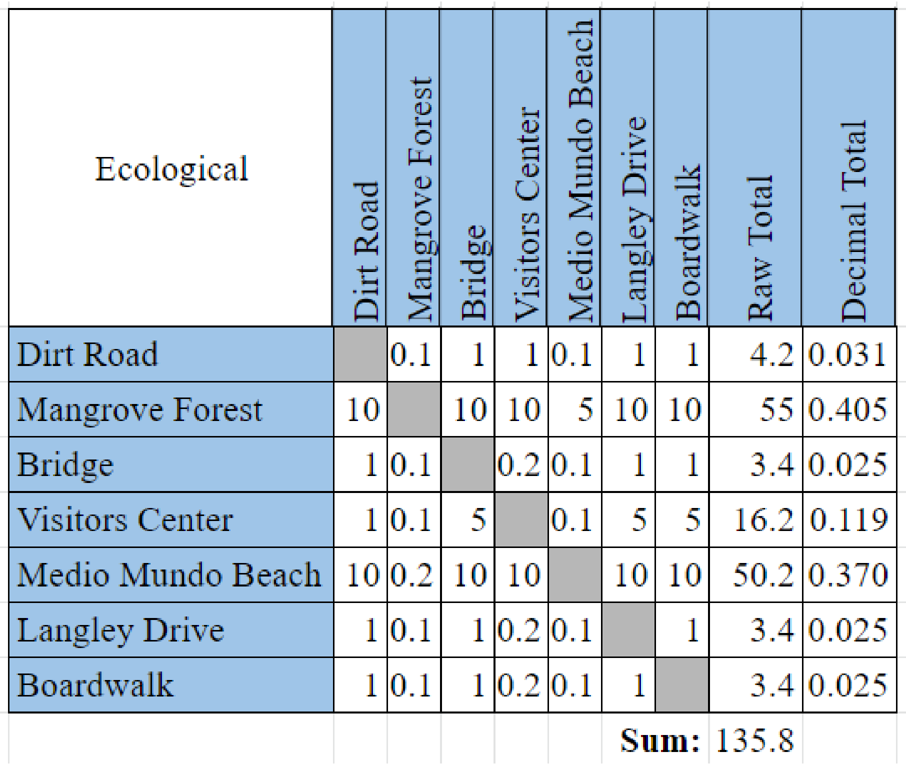
Cultural	Dirt Road	Mangrove Forest	Bridge	Visitors Center	Medio Mundo Beach	Langley Drive	Boardwalk	Raw Total	Decimal Total
Dirt Road		1	1	1	1	1	1	6	0.143
Mangrove Forest	1		1	1	1	1	1	6	0.143
Bridge	1	1		1	1	1	1	6	0.143
Visitors Center	1	1	1		1	1	1	6	0.143
Medio Mundo Beach	1	1	1	1		1	1	6	0.143
Langley Drive	1	1	1	1	1		1	6	0.143
Boardwalk	1	1	1	1	1	1		6	0.143
							Sum:	42	



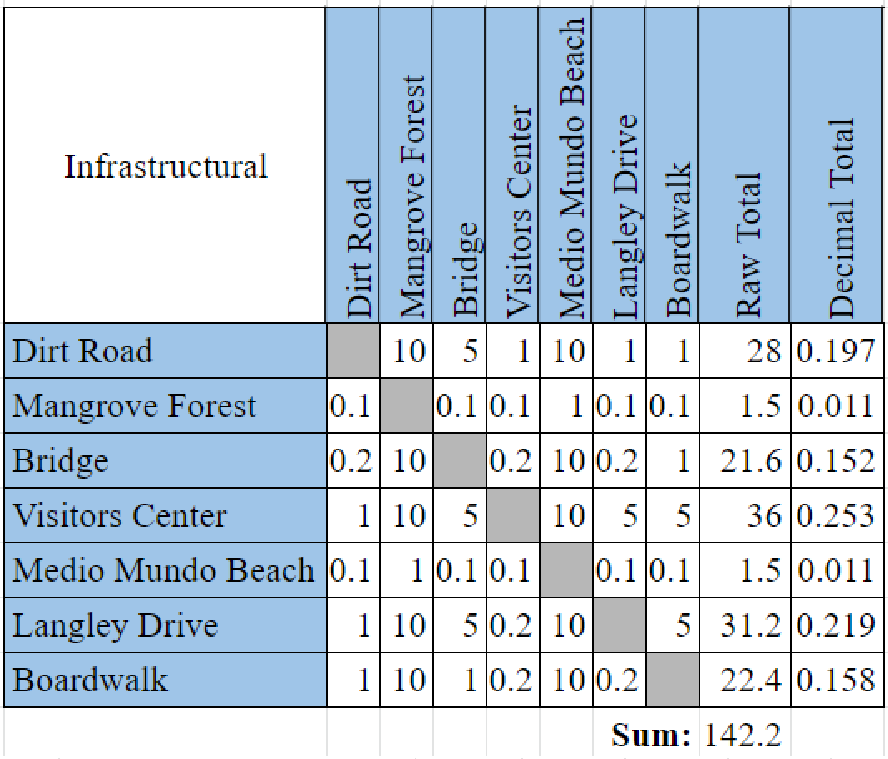
Score	Description
10	Much More Important
5	More Important
1	Equally Important
0.2	Less Important
0.1	Much Less Important



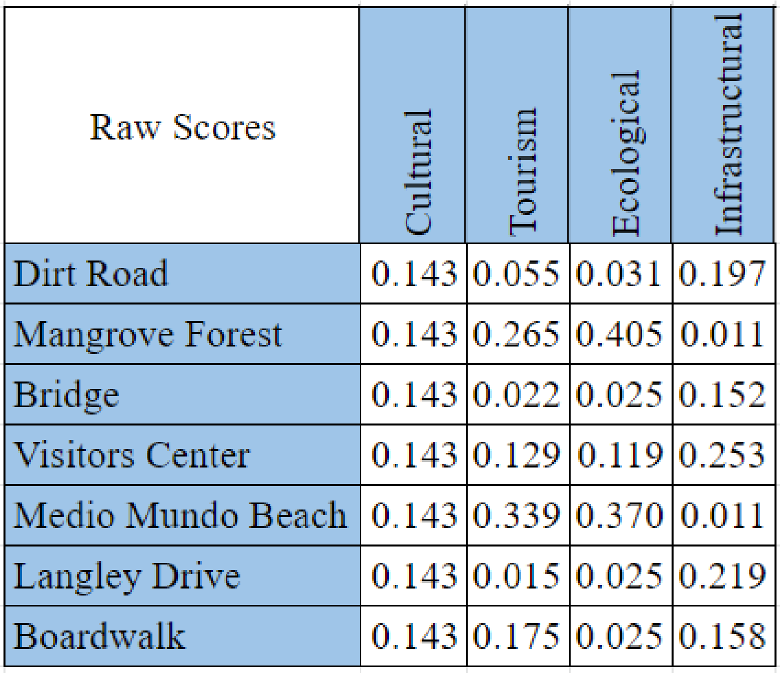
Tourism	Dirt Road	Mangrove Forest	Bridge	Visitors Center	Medio Mundo Beach	Langley Drive	Boardwalk	Raw Total	Decimal Total
Dirt Road		0.2	1	0.2	0.1	5	0.2	6.7	0.055
Mangrove Forest	5		10	5	1	10	1	32	0.265
Bridge	1	0.1		0.2	0.1	1	0.2	2.6	0.022
Visitors Center	5	0.2	5		0.2	5	0.2	15.6	0.129
Medio Mundo Beach	10	1	10	5		10	5	41	0.339
Langley Drive	0.2	0.1	1	0.2	0.1		0.2	1.8	0.015
Boardwalk	5	1	5	5	0.2	5		21.2	0.175
							Sum:	120.9	



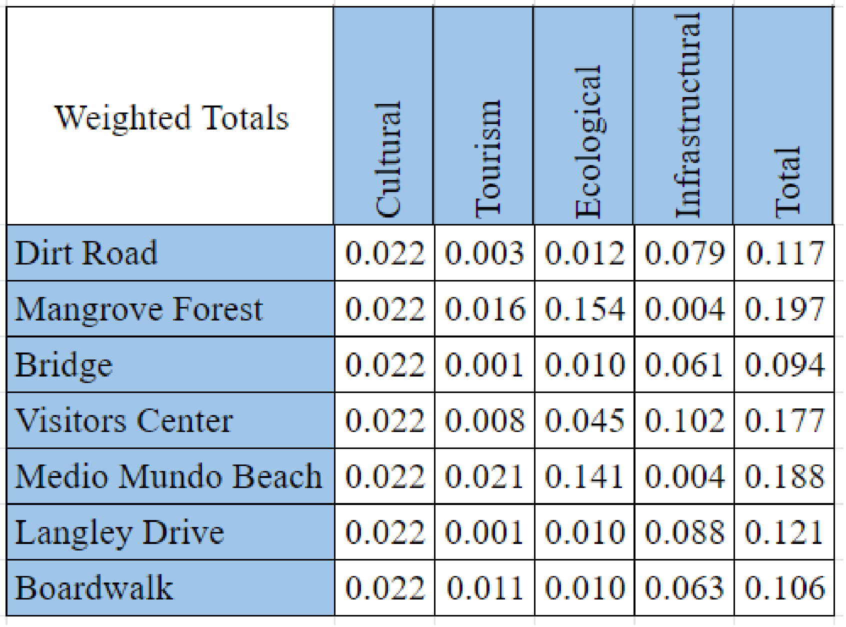
Ecological	Dirt Road	Mangrove Forest	Bridge	Visitors Center	Medio Mundo Beach	Langley Drive	Boardwalk	Raw Total	Decimal Total
Dirt Road		0.1	1	1	0.1	1	1	4.2	0.031
Mangrove Forest	10		10	10	5	10	10	55	0.405
Bridge	1	0.1		0.2	0.1	1	1	3.4	0.025
Visitors Center	1	0.1	5		0.1	5	5	16.2	0.119
Medio Mundo Beach	10	0.2	10	10		10	10	50.2	0.370
Langley Drive	1	0.1	1	0.2	0.1		1	3.4	0.025
Boardwalk	1	0.1	1	0.2	0.1	1		3.4	0.025
							Sum:	135.8	



Infrastructural	Dirt Road	Mangrove Forest	Bridge	Visitors Center	Medio Mundo Beach	Langley Drive	Boardwalk	Raw Total	Decimal Total
Dirt Road		10	5	1	10	1	1	28	0.197
Mangrove Forest	0.1		0.1	0.1	1	0.1	0.1	1.5	0.011
Bridge	0.2	10		0.2	10	0.2	1	21.6	0.152
Visitors Center	1	10	5		10	5	5	36	0.253
Medio Mundo Beach	0.1	1	0.1	0.1		0.1	0.1	1.5	0.011
Langley Drive	1	10	5	0.2	10		5	31.2	0.219
Boardwalk	1	10	1	0.2	10	0.2		22.4	0.158
							Sum:	142.2	



Raw Scores	Cultural	Tourism	Ecological	Infrastructural
Dirt Road	0.143	0.055	0.031	0.197
Mangrove Forest	0.143	0.265	0.405	0.011
Bridge	0.143	0.022	0.025	0.152
Visitors Center	0.143	0.129	0.119	0.253
Medio Mundo Beach	0.143	0.339	0.370	0.011
Langley Drive	0.143	0.015	0.025	0.219
Boardwalk	0.143	0.175	0.025	0.158



Weighted Totals	Cultural	Tourism	Ecological	Infrastructural	Total
Dirt Road	0.022	0.003	0.012	0.079	0.117
Mangrove Forest	0.022	0.016	0.154	0.004	0.197
Bridge	0.022	0.001	0.010	0.061	0.094
Visitors Center	0.022	0.008	0.045	0.102	0.177
Medio Mundo Beach	0.022	0.021	0.141	0.004	0.188
Langley Drive	0.022	0.001	0.010	0.088	0.121
Boardwalk	0.022	0.011	0.010	0.063	0.106

F.3 Raw Data from Vulnerability Based Prioritization

Vulnerability Rankings for Las Cabezas de San Juan Nature Reserve					
Area	**SLR**	**Coastal Erosion**	**Floodplains**	**EWE Vulnerability**[1]	**Total**
Road	4	1	2 (VE)	1	**6**
Seven Seas Beach	4	2	2 (VE)	1	**7**
Play Jayuya	3	2	2 (AO)	1	**6**
Playa Lirios	3	2	2 (VE)	1	**6**
Playa Canalejo	3	2	2 (VE)	1	**6**
Visitors Center	3	0	1	0	**4**
El Faro	0	0	0	1	**1**
Laguna Grande	4	0	1	0	**5**
Boardwalk	2	0	1	0	**3**

[1] This point is given to areas that are particularly vulnerable to the effects of extreme weather events because they have immediate proximity to the coast (i.e. beaches) or are located such that they are particularly exposed and/or lack protection (i.e. El Faro).

Vulnerability Rankings for Área Natural Protegida Medio Mundo y Daguao					
Area	**SLR**	**Coastal Erosion**	**Floodplains**	**EWE Vulnerability**[1]	**Total**
Dirt Road	4	2	2 (VE)	1	**7**
Mangrove Forest	4	1	2 (VE)	1	**6**
Bridge	2	0	2 (VE)	1	**3**
Visitors Center	1	0	1	1	**3**
Medio Mundo Beach	3	2	2 (VE)	1	**6**
Langley Drive	2	1	2 (AO)	0	**3**
Boardwalk	2	0	1	0	**3**

[1] This point is given to areas that are particularly vulnerable to the effects of extreme weather events because they have immediate proximity to the coast (i.e. beaches) or are located such that they are particularly exposed and/or lack protection (i.e. El Faro).