The Causeway
Bridging Disaster Relief, Recovery, and Climate Adaptation in the Rio Anton Ruiz Watershed

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The impact of natural disasters is often exacerbated by disparity between resources for immediate relief versus long-term recovery and resiliency. After Hurricane Maria struck in September 2017, many residents of the barrio of Punta Santiago in Puerto Rico lived in the remains of their homes for over a year with little resources to rebuild from the severe wind damage and flood waters that rose over 6 feet. Recovery is still underway almost two years later. As climate change leads to more intense and potentially more damaging storms, coastal communities will bear the brunt of this trend. A sustainable way forward for Punta Santiago and other coastal communities necessitates strategies ranging from living shorelines, coastal setbacks, and managed retreat. This thesis investigates the time disparate processes of disaster relief, recovery, and climate adaptation through the lens of their impact upon the interdependent identities of people and place as informed by theorists and designers including J.B. Jackson and Patrick Geddes. My approach works from the scale of the Antón Ruiz watershed to the Delta to uncover the historical and contemporary processes that knit people in the region to the land. I identify commonalities in the immediate recovery needs and long-term resiliency of the community and ecosystems, and seek to support ongoing globally significant research of the rare coastal systems surrounding Punta Santiago. The proposed design, a causeway linking the coast to the hills, dovetails disaster relief and recovery with climate adaptation by providing a persistent connection that restores and reveals the dynamic coastal landscape.
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Global warming is correlated with an increase in sea level rise, atmospheric moisture (water content in the air), and surface sea temperatures. The body of research around the complex interaction of these factors is growing, but current projections are that warmer seas will cause more intense hurricanes. Coastal communities, particularly those with fewer economic resources, bear the brunt of this trend and recovery is more difficult with each passing storm. After Hurricane Maria struck in September 2017, many residents of the barrio of Punta Santiago in Puerto Rico lived in the remains of their homes for over a year with little resources to rebuild from the severe wind damage and flood waters that rose over 6 feet. Recovery is still underway almost two years later. A sustainable way forward for Punta Santiago and other coastal communities worldwide necessitates strategies ranging from natural shore stabilization techniques like mangrove buffers and living reefs to restrictions on coastal development, and even the relocation of communities. This thesis investigates the time disparate processes of disaster relief, recovery, and climate adaptation through the lens of their impact upon the interdependent identities of people and place as informed by theorists and designers including J.B. Jackson and Patrick Geddes. My approach works from the scale of the Antón Ruiz watershed to the delta to uncover the historical and contemporary land use that knit people in the region to the land. I identify commonalities in the immediate recovery needs and long-term resiliency of the community and ecosystems, and seek to support ongoing globally significant research of the rare coastal systems surrounding Punta Santiago. The proposed design, a causeway linking the coast to the hills, dovetails disaster relief and recovery with climate adaptation by providing a persistent connection that restores and reveals the dynamic coastal landscape.
This work is dedicated to my mom, Linda Schiavoni
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The office of the United Nations High Commissioner for Refugees (UNHCR) has reported an unprecedented surge in the number of displaced people with 68.5 million worldwide as of June 2018. Climate refugees are an emerging category of displaced people who currently do not have the protection of any formal recognition under international law. And yet, an estimated average of 263.5 million people have been displaced by catastrophic weather disasters since 2008. In 2017, the 7th most active hurricane season to date, there were 18.8 million new environmental displacements with 3 million attributed largely to Hurricanes Harvey, Irma, and Maria.

While international support remains undefined for climate refugees—communities, cities, and even entire countries are testing the waters of proactive measures including coastal set-backs, managed retreat, and resilient infrastructure. In the meantime, even as planning and design professions are partnering in visions for more resilient cities, disaster relief and recovery frameworks are operating outside of these long-term plans and intensity of storms is increasing. People in vulnerable areas experience this missed opportunity for coordinated disaster relief and resilience planning as housing in-security, food shortages due to damaged agricultural land, unreliable utility services, loss of industry, and depopulation. The imperative to find landscape linkages between disaster relief and resilient city planning is clear.

Hurricane Maria led to the relocation of nearly 160,000 people in Puerto Rico to the mainland United States. Those who were internally displaced or undertook recovering-in-place faced many challenges to housing rehabilitation and the repair of basic services like water and electricity. Climate projections stand to increase and amplify these experiences of displacement in the wake of storms and as a result of sea level rise, especially in coastal communities.

This thesis investigates the time disparate processes of disaster relief, recovery, and climate adaptation through the lens of their impact upon the interdependent identities of people and place as informed by theorists and designers including J.B. Jackson and Patrick Geddes. The approach of this thesis works from the scale of the Antón Ruíz watershed to the delta to uncover the historical and contemporary processes that knit people in the region to the land. The Río Antón Ruíz Delta encompasses a coastal barrio and a wetland reserve both of which have been shaped by the Delta’s agricultural past and greatly impacted by Hurricane Maria. The future of the people and ecosystems of the Delta is uncertain. Rising sea levels will make inhabiting the lowest lying areas of the coast more precarious and even impossible over the next 50 to 100 years while the accompanying rise in saltwater intrusion into the coastal lagoon system threatens rare old-growth freshwater swamps in the reserve. This thesis seeks to apply the strengths of landscape architecture from ecologically sensitive master planning to culturally specific place-making to find synergies between ecosystem and community resilience.

I examine the management plan for the wetland reserve and the resiliency needs of the coastal communities in the Río Antón Ruíz watershed and build on their commonalities to address disaster preparedness and climate adaptation in a plan for the Delta. The goal is to facilitate climate adaptation for communities in transition through landscape design that builds connection to new resilient infrastructure so that it can become not just a functionally integrated structure, but a host for culturally significant places. By working in alliance with the temporality of ecological systems, I seek to support protection and ongoing globally significant research of the rare coastal systems surrounding Punta Santiago. The proposed design, a causeway linking the coast to the hills, dovetails disaster relief and recovery with climate adaptation by providing a persistent connection that restores and reveals the dynamic coastal landscape.

Methodologies and Application

I began the site selection process at the scale of the watershed and continued in further analysis to characterize the site through its hydrology. The watershed-based approach was inspired by the work of Patrick Geddes, specifically his contribution of the valley section and his writings on civic sociology, which argue that the “river system is…the essential unit for the student of cities and civilizations…By descending from source to sea we follow the development of civilization from its simple origins to its complex resultants.”¹ Through his seminal Valley Section, a transactional depiction of occupations and resources in a watershed, Geddes illustrated the interdependency of landscapes and societies. Though the drawing is highly reductionist as an archetypal scheme, the driving idea that culture, values, and material relationships to natural resources differ in relation to a community’s environment was revolutionary and continues to be foundational to landscape literacy.²

³ Francisco J. Vilella and Matthew J. Gray, “Ecological Assessment and Management Plan for the Humacao Wildlife Refuge,” (Department of Natural and Environmental, 1997).

The goals of this project derive from the management plan for the Humacao Nature Reserve (HNR), the wetland reserve located in the Río Antón Ruiz Delta, came from an analysis of the wetland management plan prepared for the Puerto Rico Department of Natural and Environmental Resources (PR DNER) in 1997. The authors, Dr. Francisco J. Vilella and Dr. Matthew J. Gray, represented the Mississippi Cooperative Fish and Wildlife Research Unit of the U.S. Geological Survey (USGS). Lack of funding has hindered complete execution of the plan’s recommendations, but the focus of the plan to maximize waterbird use is still the primary management goal of the reserve.³ Additionally, I was able to tour the lagoons and wetlands with its manager, Manuel Corbet, who has worked there since the creation of the reserve in 1986. He contributed substantially to my understanding of the ecological processes at work and the management strategies used to date.
I conducted a risk assessment of the habitats and communities in the Delta using reports on the U.S. Army Corps of Engineers (USACE) flood protection projects in the area and the associated proposals for saltwater intrusion measures and *Pterocarpus* restoration plantings that have been proposed to mitigate the effects of the flood protection projects. Additionally, I used publicly available geospatial sea level rise and storm surge data, which I interpreted with the help of reports from the Puerto Rico Climate Change Council (PRCCC), Federal Emergency Management Agency (FEMA), and the Coastal Zone Division of the Puerto Rico Department of Natural and Environmental Resources (PR DNER).

Reports and field photography pertaining to ongoing recovery projects in Punta Santiago post Hurricane Maria helped frame a determination of important cultural and historical landmarks. The Muelle de Punta Santiago, a fishing dock constructed in the place of a historical dock from the time of Spanish colonization and an important piece of infrastructure for the thriving fishing community in Punta Santiago, is chief among these sites. I included revitalization of the dock and surrounding area in the design goals.

This thesis seeks to create synergy between disaster relief and future planning for disaster resilience. Both goals will benefit from ecologically and culturally responsive landscapes that foster healing through preserved connections to place. The design, a vehicular and pedestrian causeway, is a public amenity that provides safe passage and continuity of resources before and after storm events. It is also an armature for a multi-functional system of restoration plantings and recreation opportunities in the wetland. The pedestrian extension of the causeway to the coast revitalizes the existing coast area retrofitting important community landmarks to accommodate changing sea levels. The design serves the immediate needs of the coastal communities and ecosystems and reveals their interconnectedness while positioning both to better adapt to climate change.
A note on the images at the beginning of each chapter:
Through these images I seek to represent the character of the Río Antón Ruíz Delta. When possible, the images are stills taken from video of driving the two roads that bound the Delta: PR-53 which stretches across the upper reaches beyond the wetland reserve and PR-3 which travels the coast. I hope by capturing the landscape in movement to communicate the shifting light and atmosphere of this special place.
Hurricanes impact every aspect of life in Puerto Rico. Storms shape the archipelago’s ecosystems and impact the economy and population dynamics as well as the access and supply of critical resources. Hurricanes are a fundamental part of life in Puerto Rico, as evidenced by the root of the word “hurricane.” The word comes from the Taino people, the prominent indigenous inhabitants from 700 AD until the arrival of Christopher Columbus in 1493.¹ The arrival of westerners spurred the decline and eventual extinction of Tainos and began the colonization of Puerto Rico which essentially persists today, despite the island having attained commonwealth status under the United States in 1952. Hurricanes have exposed the vulnerabilities created by institutional neglect under colonialism. In recent years, communities have organized around ending the resource insecurity made salient by increasingly powerful storms by developing resilient micro-systems for food, water, and power. Hurricanes are thus part of a long and unfolding narrative of disturbance, diaspora, and resistance in Puerto Rico.

Overview
Hurricane season in the Atlantic lasts from June to November with the period of August through October featuring the greatest activity. The season’s peak is in September. On average, there are 12 named storms, 6 hurricanes, and 3 major hurricanes during the Atlantic hurricane season.  

Economics
In its June 2016 report, the Congressional Budget Office (CBO) estimated a .6% increase in the costs of hurricane damage from .16% of GDP to .22% by 2017. Their calculations attribute about 45% of that increase to climate change and 55% to coastal development. The CBO also estimated that federal spending for hurricane relief will rise from .10% of GDP to .13% of GDP.  

The National Weather Bureau officially began naming Atlantic hurricanes in 1950, but records for Puerto Rico date back to 1494 with the arrival of Christopher Columbus and the first European written account of a hurricane.  

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Hurricane Maria is the costliest hurricane in Puerto Rican history and the most violent cyclone the island has experienced in over 80 years. With most of its population (2.3 million, 61%) and infrastructure concentrated on the coasts, Puerto Rico is extremely vulnerable to hurricanes. This also means that the coastal ecosystems critical for mitigating sea level fluctuations are often threatened by development.

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3.3 Map of settlement and urbanization, inundation of a Category 5 storm, and population of the 20 largest cities in Puerto Rico.

COSTLIEST HURRICANES IN PUERTO RICO

<table>
<thead>
<tr>
<th>Hurricane</th>
<th>Year(s)</th>
<th>Total Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maria</td>
<td>2017</td>
<td>$125B</td>
</tr>
<tr>
<td>Georges</td>
<td>1998</td>
<td>$68.7B</td>
</tr>
<tr>
<td>Hugo</td>
<td>1989</td>
<td>$50.0B</td>
</tr>
<tr>
<td>San Felipe Segundo</td>
<td>1928</td>
<td>$50.0B</td>
</tr>
</tbody>
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COSTLIEST HURRICANES IN US

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<tr>
<th>Hurricane</th>
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<td>1928</td>
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</tr>
</tbody>
</table>

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3.3 Costliest hurricanes in the mainland US and Puerto Rico. Values are not adjusted for inflation.
An inventory of Puerto Rico’s coastal uses and assets includes 17,387 miles of primary roads, 11 airports, 12 ports, 81 industrial parks, and 1,080 miles of sanitary infrastructure. An estimated 65 billion dollars a year of the territory’s GDP is linked to its coastlines. Focusing specifically on the critical resources of power, water, and food, the extent and significance of Puerto Rico’s reliance on coastal development becomes salient. In terms of power production, seven of Puerto Rico’s 16 power plants are located in areas of medium and high inundation. Five of these power plants are run by fuel, oil, or coal and thus carry a risk of releasing contaminants when damaged.

Contamination of surface water is an especially concerning issue because it is an important source of drinking water for the island. Puerto Rico has struggled in the past to meet water quality guidelines. The Natural Resources Defense Council conducted a review of violations received by Puerto Rico water systems from 2005 to 2015 and found that of the 466 water systems operated throughout the island, 146 violated the standards of the U.S. Safe Drinking Water Act. Water treatment facilities, industrial sites, agriculture, industrial sites are major sources of pollutants in surface water. Twenty-eight of the island’s waste water treatment plants are located in the coastal zone where they may be compromised by flooding and wind speeds of tropical storms which can exacerbate contamination.

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7 Coastal Zone Management Program, “Coastal Resiliency Building: Mainstreaming Adaptation.”
10 Coastal Zone Management Program, “Coastal Resiliency Building: Mainstreaming Adaptation.”
Under U.S. control as a territory from the late 1800s to the mid 1900s, much of Puerto Rico was intensively farmed for sugar cane. Economic shifts led to a wide-scale abandonment of agriculture and an increase in food imports.¹¹ The precarious network relies upon just two ports: Jacksonville and San Juan. Food costs are also twice as expensive in Puerto Rico as they are in Florida. Before Hurricane Maria, Puerto Rico imported around 80% of its food goods. Hurricane Maria destroyed 80% of the island’s crop value and after the storm, food imports jumped to 95%.

Community Resilience

The profound devastation wrought by Hurricane Maria exposed the vulnerabilities of the island’s infrastructure and led to the relocation of 159,415 people to the mainland U.S.12 Though this is the greatest migration to date, the population of Puerto Rico has been declining since 2005 and the Puerto Rican diaspora has been larger than the population of the island, since at least 2010.13 This trend is due in part to falling birthrates and rising death rates, but also significantly to migration triggered by the repeal of Section 936, a tax law that was a powerful stimulus for industry and employment on the island.14

Hurricanes have punctuated the steady emigration of people seeking economic opportunity. In the face of economic stagnation and its hindrance of needed resilient infrastructure, communities have escalated efforts to create their own resilient system contributing to a growing network of micro-grids and resource hubs throughout the island.

Ecology. The archipelago of Puerto Rico is part of the Greater Antilles and is comprised of many islands and cays. The largest of which are Puerto Rico, Vieques, Culebra, Mona, and Desecheo. Only Puerto Rico, Vieques and Culebra are inhabited. Puerto Rico’s physiography is highly complex. The diversity of soils and elevation support many different ecosystems among them a variety of different forests, including El Yunque.  

The Cordillera Central and Sierra de Cayey running along a roughly east-west axis across the mainland of Puerto Rico interact with winds from the east and create a window shadow: an area of decreased precipitation on the leeward side of a mountain. The south coast is drier as a result. Rain shadow winds also produce a diurnal cycling of the direction of prevailing winds. The interaction between rainfall and elevation plays a key role in the distribution of the three main regional ecosystems: tropical rainforest, mountains and hills, and grasslands.

Though precipitation varies with physiography, the island overall has a tropical wet/dry seasonal cycle. The dry season is from December to March with the driest month being February when monthly rainfall can be as low as five inches in the rainforest and around two inches for the rest of the island. The wet season lasts from April to November with a maximum peak in May and a secondary peak in October and November during the tail end of the most active months of hurricane season.16

The impact of hurricanes on the ecosystems of Puerto Rico is illustrative of the role of disturbance in landscape history. One way hurricanes have shaped Puerto Rico’s landscape is by driving the adaptation of plant communities. In general, forest architecture in hurricane prone areas is less stratified and trees are often shorter, more stout, and sculptural in appearance.

The elfin cloud forest, sierra palm breaks, mangrove forests, swamp bloodwood forests, and other distinct ecosystems in Puerto Rico have evolved their unique forms in concert with the disturbance regime of hurricanes. Hurricanes also shape the landscape through the collective effects of erosion, landslides, disease outbreaks, and other keystone processes that unfold over different time scales.17

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<th>Hurricane Related Keystone Processes</th>
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3.14 Table comparing keystone processes associated with hurricanes and their relative lengths of time to affect landscape change.
Site Selection
Working from the Watershed to the Delta

Focusing on the corridor of hurricane activity identified in the previous section and the resource of drinking water, I compared watersheds according to their forest cover, surface water supply, and protected area assessing them for a combination of elements that would facilitate an exploration of how to bridge disaster relief and resilience through nature-based infrastructure.

4.1 View of cow pasture in the coastal plains of the Antón Ruiz Delta from northbound on PR-3.
Drinking Water I identified an area of interest through its elevated risk of hurricanes and sea level rise and then framed deeper analysis of potential watersheds with an awareness of water as a resource and not just a threat. I sought to understand the provision of drinking water on the island through the landscapes that protect its supply.

Puerto Rico relies primarily on surface reservoirs for drinking water. The north and south coasts have productive aquifers. In contrast, the east and west coasts and Interior aquifers all have minor yields due to their low storage and high transmissivity, or horizontal pass through of water in the aquifer medium. Another contributing factor to the low reliability of groundwater for drinking is its vulnerability to contamination by saltwater. Along the coasts, particularly in the alluvial aquifers in the east and west, tidal actions contribute to seepage of seawater into the aquifer. Saltwater intrusion in the east coast is high in the area of the mangrove swamps at the mouth of the Río Antón Ruiz and the Río Blanco and at the mouth of the Río Candelero in the municipalities of Naguabo and Humacao.

Forests Drinking water reservoirs are fed by rainfall and seepage of groundwater into streams and rivers many of which flow through forested land. Of the 83% of drinking water that comes from surface reservoirs, just over 40% originates on forest land: a significant amount disproportional to the total area of forest cover on the island. The forest filters rainfall and runoff before it enters streams, protecting the water source for safer consumption.2

Before the 20th century, the island was covered in closed canopy forests. However, during the early years of U.S. colonial control, forest land was cleared for sugar cane production.3 Deforestation was so extensive that forest cover dropped to just 6% of the island by 1940.4 In the 1950s, the economy began to shift from agriculture to manufacturing and service industries and there was a wide scale abandonment of sugarcane fields. The abandoned fields began to return to forest.5 By 2009 forest cover was 54.7%.6 Forest cover today in Puerto Rico is about 38%.7 National Forest Service lands make up 1.2% of that figure with private and commonwealth forests comprising the remaining 37.1%.

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3 William A. Gould et al., “Land Use, Conservation, Forestry, and Agriculture in Puerto Rico.”
5 William A. Gould et al., “Land Use, Conservation, Forestry, and Agriculture in Puerto Rico.”
7 William A. Gould et al., “Land Use, Conservation, Forestry, and Agriculture in Puerto Rico.”
A Forest Service General Technical Report analyzed data from 141 public system intakes to quantify the role of forest lands in the supply of drinking water in Puerto Rico. Their model estimated that all land in Puerto Rico produced a combined 6.5 billion m$^3$/yr and forests alone accounted for 43.4% of that surface water. The researchers found that over 2 million people rely on forests for 30% or more of their drinking water and 3.6 million people, or about 97% of the population, receive some percentage of their water supply from forest lands. Due to the greater area of private and commonwealth forests, most of the forest contribution to drinking water originates on these lands.8

8 Erika Cohen et al., "Quantifying the Role of Forested Lands in Providing Surface Drinking Water Supply in Puerto Rico."

The most productive watersheds are in the highest elevations in the Sierra de Luquillo (including El Yunque National Forest) and Cordillera Central. These areas are dominated by forests and receive higher rainfall. Particularly for the Sierra de Luquillo, these conditions make the forests highly productive per unit of area. El Yunque National Forest, the only tropical rainforest in the United States National Forest Service, is located in the Sierra de Luquillo. Comprising only 1.2% of the total land area of the island, but contributing 219 million m$^3$/year of drinking water (3.3% of total surface water), the tropical rainforest produces over double the amount of water per square mile and serves almost double the amount of people per square mile compared to all private and commonwealth forests combined.9

9 Erika Cohen et al., "Quantifying the Role of Forested Lands in Providing Surface Drinking Water Supply in Puerto Rico."
Puerto Rico’s coastal population relies on water sourced from upland forests. The contributions of forests to the provision of drinking water establishes an important link between mountain ecosystems and coastal communities. I became interested in finding a watershed to study where this link could be strengthened.

**Protected Area** A critical piece of insuring the continued productivity and health of watersheds in Puerto Rico is protection. Though researchers have assessed 45% of the island as suitable for conservation and the Puerto Rico Land Use Plan sets aside 34% of the island for this use, currently only 8% of all land cover is protected. Forest communities dominate protected areas, but only 14.8% of all forest lands are publicly administered. The remaining portion is privately owned. The least protected land is the coastal plain, specifically former agricultural land.

With the diversity of wetlands, grassland, and forested coastal hills in this region, the coastal plain has the highest levels of habitat heterogeneity and biodiversity. Important terrestrial ecosystems like salt flats, mangrove forests, and wetlands on the coast also provide important ecosystem services for human communities including flood mitigation and buffering from storms.

The role of protected areas is expanding as it is increasingly understood that the wild lands we iconize and value for recreation, habitat, research, and other conservationist-minded goals, also actively support the resiliency of human communities. Examining existing protected area became a priority in site selection so I could explore the opportunities to enhance land management to prioritize resilience and climate adaptation.

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10 William A. Gould et al., “Land Use, Conservation, Forestry, and Agriculture in Puerto Rico.”
4.9 Map of east coast of Puerto Rico combining layers of analysis including emerging forests, mature forest cover, protected areas, and streams and rivers classified by percent of water from forest land.

Yellow represents rivers with a contribution from forest lands that is 25% or less and blue represents rivers with a contribution from forest lands that is 25% to 50%. The highlighted portion is the boundary of two watersheds, the Río Antón Ruiz and Río Blanco watersheds, which I identified as prospective locations for research and design.
Synthesis

The site selection process consisted of layering spatial data for emerging forests, mature forest canopy, and protected areas with rivers and streams classified by percent of water from forest land. The Humacao Nature Reserve in the Río Antón Ruíz watershed is the largest area of protected land outside of El Yunque National Forest and within the area of interest. The rivers in the area of interest fell into two categories with regards to forests: those with 25% of their water originating on forest land and those with greater than 25% to 50% of their water originating on forest land. The rivers supplying more water from forest lands in this region originate in El Yunque National Forest. There are no protected areas in the headwater streams of the rivers supplying less than 25% of their water from forests. These rivers, the Río Antón Ruíz included, have their origins among regions of emerging forests which are less mature and also less likely to be protected. 

The presence of the Humacao Nature Reserve and the high concentration of emerging forests made the Río Antón Ruíz a prime candidate in site selection because these characteristics suggest the importance of protecting critical ecosystems in recovery and the potential to link ecosystem services with coastal community resilience. I considered other factors including storm surge, flooding, and urbanization and compared their distribution in the Río Antón Ruíz and Río Blanco watersheds.

14 Erika Cohen et al., “Quantifying the Role of Forested Lands in Providing Surface Drinking Water Supply in Puerto Rico.”
Though both the Río Blanco and the Río Antón Ruíz have coastal communities and are prone to flooding and vulnerable to storm surge, ultimately I chose to study the Río Antón Ruíz due to its more direct relationship to the wetland reserve and the status of the forests in the watershed. The abundance of under protected regenerating forests in the environs of the upper watershed increases the importance of management in the reserve and could be the foundation for future proposals to link networks of protected areas throughout the watershed.

*Río Antón Ruíz Watershed Overview* The drainage basin of the Río Antón Ruíz watershed is 19.89 mi² and includes the three towns of the coastal barrio of Punta Santiago: Las Parcelas, Verde Mar, and Villa Palmira, which are positioned between the Caribbean Sea and a large freshwater lagoon system.15

The main regions of the watershed are the coastal hills, the coastal plain, the lagoons, and the coast itself. The coastal plain has vast alluvial regions created over many years by the deposition of sediment from rivers and streams originating in the highlands. Where the Río Antón Ruíz meets the Caribbean Sea, sediment has built over time to create a Delta, a landform which encompasses the reserve as well as the coastal barrio of Punta Santiago and the towns of Las Parcelas, Verde Mar, and Villa Palmira.

The current extent of protected land in the Río Antón Ruíz Watershed is the 1046 acre Humacao Nature Reserve bounded in the north by Río Blanco, the east by Vieques Sound, the south by Santa Teresa farm, and the west by upland pasture. Recognized as a part of the National Estuarine Sanctuary Program in 1986, Humacao Nature Reserve (HNR) represents the remnants of the freshwater wetlands that existed before the area was drained for sugar cane production in the 1920s with a system of canals, pumping stations, levels, and diversion channels.\(^{16}\)

Coastal lagoons reformed in the Delta when Hurricane David and Tropical Storm Frederick breached the levees in 1979. The resulting wetlands were preserved through the creation of Humacao Nature Reserve.\(^{17}\) Today, the reserve is comprised of six lagoons: Mandri 1 (166 acres), Mandri 2 (183 acres), Mandri 3 (128 acres), Santa Teresa 1 (67 acres), Santa Teresa 2 (59 acres), and Palmas (12 acres). The Mandri system has intermittent tidal influence, while the Santa Teresa system is largely isolated from the sea.\(^{18}\)

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\(^{17}\) Francisco J. Vilella and Matthew J. Gray, "Ecological Assessment and Management Plan for the Humacao Wildlife Refuge."

4.19 Collaged map of main ecosystems in the Río Antón Ruiz watershed.
4.20 Collaged map of land use and main highways in the Río Antón Ruiz watershed
4.21 Map of alluvial deposits in the valleys of the Río Antón Ruiz watershed with boundaries of the watershed and Humacao Nature Reserve.
Punta Santiago is a microcosm of the landscape paradigms of Puerto Rico. Shifts between different periods of land use corresponded to the larger historical trends of the entire island. At different points, the Delta has supported fishing, agriculture, and most recently eco-tourism, but the transitions between different relationships to the land have meant trade-offs between the safety and economic vitality of a community and ecological health. Flood measures that were put in place have contributed to significant environmental changes. Hurricanes have also triggered shifts, including the reformation of lagoons. As I researched and mapped the Delta, situating these landscape trends in time and space, I looked for similarities between the resiliency needs of human communities and habitats with the intention to design from a paradigm of synergy with the landscape instead of trade-offs.
Indigenous Settlement

Sandy soil deposited in parallel curves inland of the existing coast suggest that the population slowly filled in and formed wetlands, likely by sediment trapping in mangrove lagoons. The soil deposits are emphasized today by rows of coconut palms from abandoned plantations around the mouth of the Añasco del Oeste and Fronton Creek, and by El Faro, a promontory and WWI bunker south of Punta Santiago. It may have been that the coconut plantations were located on the ridges because the sandy soil deposits provided agreeable planting conditions for the crops. This image shows a cross section of the historic shoreline in Punta Santiago made from a study of soil deposition from aerial imagery.

US Colonization

In the first 50 years of US colonization, the economy of Puerto Rico was based on agriculture, primarily sugar cane. Plantation agriculture led to wide-scale deforestation. The abandonment of fields led to widespread forest degradation with significant portions of the swamp bloodwood forest. Sugar cane was grown in the wetlands surrounding Punta Santiago. Coconut palms were planted on the coast. A system of levees, canals, and a pumping station was constructed to drain the wetlands and control periodic irrigation of the fields. The crop was transported nearby via a train that cut across the fields to the mill in Pasto Nuevo. The mill used to process sugar for export. The Porta Puer luca sugar workers, given plots in Las Parcelas, was a common practice among the plantation owners, but is riddled with corruption and hamstringed by a lack of job opportunities in the rural areas where land was allowed.

Coastal Lagoon Reformation

In 2001, the United States Army Corps of Engineers (USACE) completed a flood control project in Punta Santiago that entailed the construction of a levee along the eastern edge of Las Palmas and Verde Viejo, an drainage canal on the inside of the levee, excavation of the Boca Prieta channel, and a new diversion channel dug from the large Mandri lagoon to the sea which also received water from the Boca Prieta channel. The diversion channel was dug much smaller and deeper than originally planned and did not close seasonally like the Boca Prieta had previously. The sustained connection between the lagoons and the sea caused substantial increases in salinity which have led to tree deaths in the swamp bloodwood forest and an increase in mangroves. The USACE-intended temporary sedimentation wells as salinity mitigation measures and observed a decline in salinity. When Hurricane Maria struck in 2017, it caused a storm surge that reached near four feet. Mangrove forests on the coast are the main defense against storm surge. They suffered moderate mortality in Hurricane Maria, but according to a FEMA assessment should recover fully with active management. A few new buildings elevated on stilts and built to the latest construction standards, performed well in Hurricane Maria, but most development in Punta Santiago, especially Las Palmas, is older and vulnerable. We do not discount that they could not uncover a resiliency plan for Punta Santiago. It is uncertain how long conditions will be sustainable without climate adaptation.

5.2 Timeline of landscape change in Rio Antón Ruiz Delta and historical events in Puerto Rico.

650

650

ca. 1493

1492

ca. 1800

1520

1550

1750

1850

1952

2013

2019

[Image 513x450 to 619x578]
**Hydrology** The towns in the Río Antón Ruíz Delta have historically faced serious flooding in all seasons from both upland runoff and coastal inundation. The headwater streams of the watershed swell with runoff from the mountains, flow across the coastal plain into a freshwater lagoon and forested swamps before flooding the coastal communities and emptying into the sea through two outlets: the Río Antón Ruíz and the Boca Prieta. Storm surge can cause flooding as high as 12 feet and reaches as far as the edge of the reserve at the foot of the coastal hills. During Hurricane Maria, water levels between seven to nine feet were recorded in Las Parcelas.

A flood control project completed in 2001 by the U. S. Army Corps of Engineers addressed upland runoff by redirecting floodwater from the lagoon around the communities to the sea through the two existing outlets. The system was designed for a ten-year storm and included a 2.25 mile long levee with an Interior drainage canal running along the western border of Punta Santiago and Verde Mar, a diversion channel, and a culvert connecting the drainage canal to the diversion channel. The canal collects stormwater from the communities and delivers it to the Boca Prieta outlet. The culvert provides an additional outlet for Interior drainage by connecting the canal to the diversion channel which empties at the Río Antón Ruíz outlet.

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17 David and Velez, Rafael Weston, “Controlling Salt-Water Intrusion to Environmental Sensitive Areas Due to the Construction of the Río Antón Ruíz Flood Control Project.”
19 David and Velez, Rafael Weston, “Controlling Salt-Water Intrusion to Environmental Sensitive Areas Due to the Construction of the Río Antón Ruíz Flood Control Project.”
5.4 Map of the different magnitudes and time scales of water movement that make up the hydrology of the Río Antón Ruiz watershed.
Habitats

The upper regions of the Delta were previously subtropical moist forests which have been largely deforested in the Río Antón Ruiz watershed and throughout Puerto Rico as a whole. Subtropical moist forests are one of the most intensively used life zones in the tropics because their regular rainfall and generally fertile soils, except in karst regions, make it suitable for agriculture.\(^\text{20}\) The absence of subtropical moist forests in the foothills and coastal plains in the Río Antón Ruiz watershed increases runoff from steep mountain slopes which contributes to inland flooding along the coast. This trend is compounded by the decline in agriculture in Puerto Rico. Less water is consumed in coastal plains and upland regions for agriculture meaning there is more freshwater runoff in public water systems and lagoons in coastal zones. Protecting the emerging forests on abandoned fields and pastures in the Delta will help detain and filter runoff.\(^\text{21}\)

One of the most important ecosystem services of the freshwater wetlands of the Humacao Nature Reserve is to regulate flood water by serving as a detention area for upland runoff. The wetlands filter this water and, in tidal areas, the dilution of the saltwater from freshwater input is critical to support endangered forests and commercially as well as culturally valuable hunting and fishing land.\(^\text{23}\) Punta Santiago, the oldest of the coastal communities was originally a small fishing village and though sugar production in the 1900s and now light industry provide most jobs in the area, fishing is extremely important to the identity of residents, largely because of the connection it offers to nature. One study found that 86% of anglers come to Humacao Nature Reserve to primarily explore in nature and secondarily, to fish.\(^\text{24}\) Small business owners rely on the reserve as an attraction for tourists, an economy encouraged by Ecotourism Initiative of Humacao (INECOH) which co-manages the reserve with the Department of Natural and Environmental Resources.\(^\text{25}\) The National Estuary Sanctuary Program describes the research value of the Pterocarpus forests and other freshwater systems in the reserve as “almost incalculable” and the uniqueness of the vegetation and wildlife as an experience that offers educational value for school children and graduate students alike.\(^\text{26}\)

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\(^\text{21}\) Ricardo J. Colón, “Saltwater Incursion into Micro Tidal Wetlands: Case Studies from Matagorda, Texas and Humacao, Puerto Rico.”
\(^\text{22}\) David and Velez. Rafael Weston, “Controlling Salt-Water Intrusion to Environmental Sensitive Areas Due to the Construction of the Río Antón Ruiz Flood Control Project.”
\(^\text{23}\)监督检查科，arkin\text{“Saltwater Incursion into Micro Tidal Wetlands: Case Studies from Matagorda, Texas and Humacao, Puerto Rico.”}
\(^\text{24}\) Orlando J.; Dibble Ferrer Montaño, Eric D.; Jackson, Donald C.; and Rundle, Kirk R., “Angling Assessment of the Fisheries of Humacao Natural Reserve Lagoon System, Puerto Rico.”
\(^\text{25}\) Francisco J. Vilella and Matthew J. Gray, “Ecological Assessment and Management Plan for the Humacao Wildlife Refuge.”
5.6 Map of the habitats in the Río Antón Ruíz Delta as well as the main features of the USACE flood control project and boundaries for land ownership by public entities.
5.7 Sections of existing conditions in the different areas of the Delta.
5.8 Map of past and present infrastructure in the Delta.
5.9 Entrance to the Humacao Nature Reserve on PR-3

5.10 Hurricane evacuation signage on PR-3 near entrance to the reserve.

5.11 Pumping station

5.12 Old canal lock

5.13 Old footings of locks on Mandri canal

5.14 Canal connecting Mandri 1/2 and Mandri 3 showing new mangrove growth since salinity increased. Also evident in this photo is hurricane damage especially to mangroves on the water's edge.

5.15 Sewer, water, and power lines along PR-3 from bridge over the mouth of the Río Antón Ruiz

5.16 View from PR-3 just north of the mouth of the Río Antón Ruiz showing hurricane damage to palms in abandoned coconut plantations and a new electrical pole installed on the landward side of the road.
Community Resilience Needs Today, upland flooding is much less of a problem in Punta Santiago. Instead, coastal threats like storm surge, sea level rise, and erosion have risen to the forefront, most notably in the aftermath of Hurricane Maria. A majority of the town is located in a high risk flood area according to FEMA Flood Insurance Rate Maps. Pedro Morales Oquendo, the Vice President of PECES, a nonprofit headquartered in Punta Santiago, is quoted as estimating that 100 percent of the buildings in the barrio were damaged in Maria. A pilot study assessed the community needs and mental health status of Punta Santiago. Even after six months, power had been restored to only 10% of the study population and two-thirds relied on bottled water as their primary drinking water source. The devastation of the hurricane was exacerbated by the difficult economic conditions in Punta Santiago. The population of the barrio is older and the average median income is lower than the mainland U.S. and the island of Puerto Rico. Many residents are retired or unemployed and receive federal support. The same community health study found that post-Maria, the already high unemployment rates in Punta Santiago dropped 20% and there was a 54.1% prevalence of depression which is three times the island wide prevalence of depression in 2016 (18.2%).

The town most impacted by Hurricane Maria was Las Parcelas, the oldest of the three communities and the heart of Punta Santiago. A model of existing topography illustrates the low-lying areas around the collection points for stormwater in Las Parcelas, the drainage canal and the Boca Prieta canal. These areas, as shown by storm surge and sea level rise data, are especially prone to flooding. The U.S. Army Corps of Engineers conducted an analysis of local sea level rise data as well as other water related impacts to the town following Hurricane Maria.

5.23 Model of existing topography in Las Parcelas.
rise for the north and south coasts for the Puerto Rico Climate Change Council (PRCC) report on the state of the climate. Given the global rate of sea level rise (1.7 mm/year or .067 inches/year), their calculations predicted a rise of .5 to 6 feet by 2115. At these rates, the island can anticipate a rise of .2 to 1.87 feet within the 50 year planning horizon and a rise of .4 to 5.59 feet within the 100 year planning horizon.

To contextualize this change, the PRCC report emphasizes that sea level rise is likely to be less gradual than anticipated and will be associated with increases in tide extremes and storm surges. The report concludes that “it is no longer a question of whether the coasts of Puerto Rico and many port cities in the Caribbean will be inundated, but rather a question of when and by how much.”

In Punta Santiago, a five or six foot rise in sea levels would render the town of Las Parcelas uninhabitable.

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Las Parcelas is also the most vulnerable area for storm surge. Inundation in the lower areas of the town can occur with a Category 2 hurricane. In stronger hurricanes, the town is completely flooded with the highest water levels in the vicinity of the fishing pier where the lowest part of the beach forms an inlet and back along the drainage canal and the Boca Prieta. The adjacent town of Verde Mar, which is built on fill, is affected by Category 4 and 5 storm surge.
Using the storm surge data, I delineated risk zones for the most vulnerable areas of Punta Santiago, the coastline and Las Parcelas. The areas of severe risk are the most prone to flooding and have the highest water levels in a Category 5 storm. PR-3 is the main roadway connection for Punta Santiago. It functions as the hurricane evacuation route for the barrio, however, is itself very vulnerable to storms. The bridges over the Río Antón Ruiz and Boca Prieta outlets are above flood levels, but the road approaches are still subject to flooding. In the late 1980s, the Federal Highway Authority and the Puerto Rico Highway Authority proposed relocating the segments of PR-3 in Punta Santiago where the road is closest to the coast, further west to higher ground in the valley. Relocating PR-3 would isolate Punta Santiago and threatened its small tourism economy. When I visited Punta Santiago in January of 2019, repairs to electrical poles were still underway along PR-3. The new poles were relocated to the other side of the roadway, a seeming gesture of road repair rather than a substantive measure of protection.

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5.26 Risk map of Las Parcelas and Punta Santiago coastline.

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6 Orlando J.; Dibble Ferrer Montañó, Eric D.; Jackson, Donald C.; and Rundle, Kirk R., “Angling Assessment of the Fisheries of Humacao Natural Reserve Lagoon System, Puerto Rico.”

Since Hurricane Maria, a number of public projects have been undertaken to help the area recover. The International Primatology Association established Project Monkey Island to rebuild Cayo Santiago, a facility for research primates off the coast of Punta. They have conducted three trips to repair infrastructure at the facility and rebuild homes in towns. PECES has also responded to the housing crisis by helping residents with home repairs. The municipality of Humacao requested 7 million dollars from state Housing Department to repair the Muelle de Punta Santiago, the villa of the local Fishing Association, and other facilities integral to the fishing industry including a boat docking area, kiosks, and a fish market. Restoring access to fish is critical to the fisherman collective as well as the restaurants that support the tourism economy in Punta. Para Ti, an initiative begun by Beatriz Rosselló, the First Lady of Puerto Rico, for the recovery of economically disadvantaged areas post-Maria, conducted a series of projects in Punta Santiago. Signs around town point out the program's hand in repairs to the community park, state subsidized vacation complex, and the old WWII era structures on top of El Morrillo, and popular hiking destination in the reserve. The efforts of Fortaleza Para Ti are aimed at making Punta Santiago a tourist attraction to help life the community from economic stagnation. Unfortunately, some of the projects remain unfinished and have had little impact aside from beautification.

5.28 New mural on the Old Customs House.

5.27 Mural and picnic area on the WWII bunkers on El Morrillo in the south of the St. Teresa portion of Humacao Nature Reserve.

5.29 Plans for house repairs from Project Monkey Island work trip in January 2019.

5.31 Mural by the famous artist ROA underneath PR-3 at the mouth of the Río Antón Ruiz river.

5.30 Welcome message on a corner in Las Parcelas. Stranded without electricity or cell phone reception five days after Hurricane Maria, residents wrote “S.O.S. Necesitamos Agua/Comida” on a corner in Las Parcelas. At the one year anniversary of the storm, the faded S.O.S was transformed into a welcome message as part of a campaign by the travel company, Discover Puerto Rico, called “Cover the Progress.”

5.32 New entry sign for the barrio on PR-3.

8 “About This Project,” Project Monkey Island, https://projectmonkeyisland.org/about-this-project/.


**Habitat Management Goals**

The greatest threat to the habitats of the Humacao Nature Reserve is saltwater intrusion. The U.S. Army Corp of Engineers flood control project has not performed entirely as expected and environmental impacts to the freshwater ecosystems has been greater than anticipated. Before the construction of the diversion channel, an equilibrium of salinity was maintained by seasonal sedimentation patterns. During the dry season, when river flow and velocity were low, a temporary sand bar formed at the mouth of the river. Since the completion of the flood control project, the Boca Prieta outlet has not opened while the increased flow and velocity of water from the diversion channel has largely kept the Río Antón Ruiz outlet opened, allowing more saltwater than originally calculated to flow back into the freshwater lagoons. Salinity levels in the lagoons have quadrupled. What were once characterized as nearly freshwater, or oligohaline, lagoons (salinity of 0-5 ppt) are now more brackish. The Typha marsh has been replaced by mangroves which out-compete emergent freshwater and salt marsh vegetation in higher salinities. Globally, sea level rise is contributing to the conversion of salt marshes, and freshwater marshes exposed to saltwater intrusion, to mangrove forests. Some marsh communities are able to sustain themselves by migrating further from the coast as far as the limits of coastal development will permit. The vicinity of the Humacao Nature Reserve is privately owned and kept in pasture or farmland prohibiting migration of the marsh community.

Saltwater intrusion has also risen in the river itself, with saltwater flowing 3,280 to 4,921 feet into the freshwater forest, killing Pterocarpus trees along the channel. In the river channel, saltwater moves underneath the less dense freshwater in a wedge shape, sloped downward in an upstream direction. Salinity levels in the river channel exhibit tidal and seasonal variation with high salinity at high tide and during the dry season when a low flow rate in the river channel permits the inland movement of a saltwater wedge. The increase in freshwater input during the wet season during the dry season keeps saltwater at bay, leading to brief decreases in salinity. However, the sustained salinity is higher year round, especially in the combined mouth of the diversion channel and the Río Antón Ruiz. Subsequent projects by the USACE have aimed to mitigate saltwater intrusion and restore lower salinities in the wetland and Pterocarpus forest. Sandbag weirs installed as temporary saltwater intrusion measures delivered some promising improvements to salinity levels. Proposals to install permanent concrete capped notched weirs have been created, but lack funding. The USACE’s Feasibility Report and Environmental Assessment for the continued work on the Río Antón Ruiz Restoration acknowledges that adaptations will need to be made to the flood control system to insure continued effectiveness as sea levels rise, but the impact of hurricanes is not addressed. The feasibility report was written in early 2017 before Hurricane Maria, a disaster that made salient the serious vulnerabilities of Puerto Rico’s infrastructure systems and the unsustainability of coastal development.

There is also a plan to establish a new stand of Pterocarpus trees as a mitigation for the damage done to the existing forest. The two sites proposed for mitigation are in an existing freshwater herbaceous marsh near the Pterocarpus forest unconnected to the lagoon system. They are currently managed as pasture. The design proposal for the mitigation planting gives specific planting recommendations. The proposal advises to plant Pterocarpus saplings in mounds imitating the hummocks the trees naturally form by trapping sediment in their buttress roots. The mounds should be 12 to 18 inches high, 36 inches wide, and spaced 6 meters or about 20 feet on center. In between the Pterocarpus saplings, pond apple (Annona glabra) should be planted 3 meters or about 10 feet on center to provide shade. The pond apple should be planted a year before the Pterocarpus so that they can mature to a height of 1 meter. Pterocarpus saplings are available commercially. It is also possible that natural recruitment will occur from the nearby forest.

13 David and Velez, Rafael Weston, “Controlling Salt-Water Intrusion to Environmental Sensitive Areas Due to the Construction of the Río Antón Ruiz Flood Control Project.”
14 Ricardo J. Colón, “Saltwater Incursion into Micro Tidal Wetlands: Case Studies from Matagorda, Texas and Humacao, Puerto Rico.”
16 David and Velez, Rafael Weston, “Controlling Salt-Water Intrusion to Environmental Sensitive Areas Due to the Construction of the Río Antón Ruiz Flood Control Project.”
Disconnected section of river
Levee restricting floodplain
Old canals syphoning off freshwater

Proposed saltwater intrusion measure (SWIMs): concrete capped weirs

1.5 mi

5.33 Map of habitat changes in Delta.
5.34 Mouth of Río Antón Ruiz (right) and connection with diversion channel (left).

5.35 View facing south from PR-3 at bridge over mouth of the Río Antón Ruiz.

5.36 View of culvert on the side of the diversion channel.

5.37 View of culvert on the side of the Boca Prieta.

5.38 View of drainage channel from the levee.

5.39 View from the top of the levee which is 9-10ft above sea level.

5.40 Drainage outlet on the beach.

5.41 Coastal erosion south of the Muelle.
The spread of mangroves and loss of freshwater and salt marshes represents the loss of important habitat for the wildlife in Humacao Nature Reserve. Increasing waterbird use is the primary objective of land management in the reserve. Native duck species use the reserve as breeding, nesting, and rearing grounds and migratory species use it as overwintering. A healthy matrix of grassland and hemi-marsh should be maintained to support these populations. The HNR Ecological Assessment and Management Plan outlines strategies for creating functioning wetland management infrastructure. The report advises a system of moist-soil management to preserve open grasslands which are preferred by a number of species for nesting. Moist-soil management entails suspending succession in a wetland through a schedule of flooding, disking, and burning that prevents overgrowth and the establishment of woody species. Grasslands are not only important nesting habitat for many waterbirds, but they also provide a source of food for seed foraging species. Humacao Nature Reserve has cooperative arrangements with local cattle ranchers to allow their herd to graze within the reserve as a passive management strategy for moist-soil zones. Studies of similar arrangements exist in the wetlands of the Paraná River and studies have observed that in addition to controlling woody species, cattle create microhabitats for invertebrates, and thus provide another food source for wildlife, when the depressions from their hooves fill with water from the saturated soil.

19 Francisco J. Vilella and Matthew J. Gray, “Ecological Assessment and Management Plan for the Humacao Wildlife Refuge.”
Another habitat important for supporting waterbird use is the hemi-marsh. Whereas moist-soil areas are seasonally drained, the water to vegetation ratio in hemi-marshes is maintained around 50:50 and drained over a longer cycle. Some species that nest over water prefer hemi-marshes because the presence of relatively small bodies of water and vegetation in close proximity provides ease of access to the water for their young while offering some visual isolation, unlike the relatively exposed large lagoons. The maintenance regime for hemi-marshes is a cycle of long periods of continuous flooding and then every 5-10 years complete drainage sustained for about a year. Draining the hemi-marsh encourages plant growth which is slowed during periods of inundation.

The land management plan recommends the construction of a series of levees to aid in the creation and maintenance of moist-soil and hemi-marsh zones. Though the levees increase control of the wetland hydrology, they are expensive to build. As of my visit in January of 2019, the reserve had only been able to construct two impoundments as pilot projects. Aside from difficulties in acquiring funds, the management staff also has problems keeping water out of the impoundments due to interactions of the new levees with existing remnants of levees and canals from the agricultural period of the Delta. Improvements including more excavation and the installation of additional water control structures are needed.

21 Francisco J. Vilella and Matthew J. Gray, “Ecological Assessment and Management Plan for the Humacao Wildlife Refuge.”
Past landscape alterations have an impact on the *Pterocarpus* forest as well. The portion of the Río Antón Ruiz approaching the reserve was channelized to prevent flooding of agricultural fields. Today, the river’s flow is decreased by the leftover network of old canals that syphon off water from the main channel. As a result, there is less freshwater reaching the *Pterocarpus* forest. Based on data of the tidal and seasonal fluctuations in salinity of the river channel, research suggests freshwater input plays the most significant role in salinity levels of the river. This finding is critical because it means that a possible strategy for dealing with saltwater intrusion as a result not only of the flood control project but also of rising sea levels is to improve hydrologic connectivity throughout the watershed, but most importantly in these highly altered areas of previous agricultural land use.

*Pterocarpus* have natural adaptations to long periods of saturation that help them to survive in regions where soil and water salinity reach their upper bounds of tolerance. They sequester salt in their rachises to protect their leaves. They have large buttress roots that according to a study of another *Pterocarpus* stand in western Puerto Rico can at their highest average 20ft tall. The formation of hummocks around these buttress roots creates unsaturated zones and lower salinity in the upper portions of the soil. Trees also develop a high concentration of shallow roots that draw water from the top two feet of soil. By moundng soil around themselves and restricting the depths of their water usage, *Pterocarpus* trees create hospitable microsites. Downed trees in Humacao Nature Reserve exhibited finer, shorter roots around their buttress roots supporting this theory. Adult trees tend to handle increases in salinity better than young trees. Though an adult may survive, they are often not replaced because leaf litter, fruit production, and flower production are all lower in high soil salinity. Planting saplings with time for the stand to mature before sea level rise begins to impact soil salinity is critical to success of restoration projects. The *Pterocarpus* forest at Humacao Nature Reserve has contributed significantly to the body of knowledge about this endangered plant community. There is much still to be learned from these forests especially about the species’ mechanisms for adaptation to climate change.

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22 Ricardo J. Colón, “Saltwater Incursion into Micro Tidal Wetlands: Case Studies from Matagorda, Texas and Humacao, Puerto Rico.”
23 Ricardo J. Colón, “Saltwater Incursion into Micro Tidal Wetlands: Case Studies from Matagorda, Texas and Humacao, Puerto Rico.”
The breadth of climate adaptation strategies ranges in its impact on existing coastal developments. Thus, community-driven decision making is very important to ensure buy-in, especially when relocation is under consideration. Sea level rise projections and the compounding damage of increasingly powerful storm surges suggest that managed retreat may be a path forward for Punta Santiago. Precedents of community relocation provide insight on important design and planning considerations for a decision of this magnitude. Chief among them are land tenure, respect for community culture, and direction by local stakeholders.

The Isle de Jean Charles resettlement project is an important and ongoing case study of community relocation that many climate-vulnerable populations follow closely. Inhabited primarily by members of the Isle de Jean Charles Biloxi-Chitimacha-Choctaw Tribe (IDJC), the Isle de Jean Charles has lost 98% of its land to coastal erosion and rising sea levels. Similarly to Punta Santiago, the isle is accessed by a single road that frequently washes out in storms and requires repair. Every hurricane that strikes the region displaces more of the residents who have survived atrocities including the Indian Relocation Act of 1830 and discrimination of the Jim Crow era, and have a deep connection to the land. Though most of the 600 members of the tribe have relocated or are no longer permanent residents, 34 families remain and many more maintain close ties to the island. The state of Louisiana received a 92 million dollar grant for resilience projects as a winner of the National Disaster Resilience Competition conducted by the U.S. Department of Housing and Urban Development (HUD). Of these funds, 48 million are earmarked for the relocation of the IDJC tribe who submitted an application under the state. The Isle de Jean Charles resettlement is meant to be directed by the tribe and the goal as summarized by congressman Tanner Magee who represents the district including the isle, is “to move an environmentally vulnerable group of people who lack enough means to move and, at the same time, maintain the group’s cultural identity as best as can be.”

However, the tribe recently withdrew from the resettlement program, triggered by the states decision to include as a provision of resettlement the requirement that recipients of new homes give up ownership of their homes on the isle. They would be permitted access for recreation and visits only. The tribe had been preparing to relocate for 20 years prior to receiving the grant. They worked closely with landscape architects on a master plan for the new community that was ecologically sensitive, self-sustaining, and celebratory of the tribe’s landscape values and connections. Though the state has purchased land for the project and the resettlement is slated to continue, without the buy-in of the tribe its success is uncertain. For its part, the IDJC is seeking alternate funding that will allow them to pursue resettlement according to their own terms. The trials of the Isle de Jean Charles resettlement project are a testament to the importance of autonomy and property to communities undergoing the challenging process of relocation.

San Juan is the site of an internationally recognized resettlement project structured around insuring land tenure. The Cano Martin Pena Restoration Project and Community Land Trust are the joint effort of over 30 public and private entities to restore the health of a watershed and improve the quality of life for communities along the channel. Awareness of the degrading quality of the Martin Pena channel and its significance to the health of the San Juan Bay estuary, the only tropical estuary in the Environmental Protection Agency’s estuary system, led to a planning proposal to dredge the trash, sediment, and raw sewage that clog the channel. Pollution and a lack of sufficient wastewater infrastructure in the vicinity of the Martin Pena channel both exacerbated by frequent flooding had created an environmental and health crisis for the 1500 to 1800 people living on its banks. These families stood to benefit from the restoration of the waterway, if they were not displaced. As members of informal settlements dating back to the 1930s, residents often had no deed for their home or land. And so, despite having occupied their homes for years and sometimes generations, they were vulnerable to forced relocation. The Community Land Trust formed to ensure that Cano Martin Pena residents are not displaced by the canal restoration projects. Members of the land trust hold collective title to their land in perpetuity. The Trust also helps residents attain proper permitting and deed documentation for their homes. Collective ownership of the land keeps prices affordable for residents and allows the land trust to sustain itself by renting properties and developing vacant lots all through a leadership body comprised of members. The estuary restoration necessitated the relocation of 1,500 families. As land trust members, they have the option to rebuild within the trust boundaries. In addition to restoration work planned for the channel, the comprehensive plan for the area calls for an extensive green infrastructure network which a landscape architecture

Theoretical Approach and Precedents


firm Spackman Mossop Michaels has been contracted to design. The Community Land Trust is an innovative mechanism that makes it possible for critical ecological restoration to be conducted and enables current residents of the compromised area to remain and enjoy the benefits of its improvement. The Cano Martin Pena project is an excellent example of linking the resiliency measures for ecosystems and communities.

While healthy wetlands, estuaries, and coastlines buffer communities from the impact of storms and mitigate flooding, there are documented precedents of natural areas also playing a direct role in services for disaster recovery. In the wake of hurricanes and other disasters, natural systems can incur substantial damage, but are likely to recover more quickly than conventional infrastructure. Urban wetlands were used extensively in the Chilean city of Concepcion for water extraction and temporary settlements following a devastating earthquake and tsunami in 2010. Upland areas in the city Dichato, Chile became important vantage and gathering points. In both of these examples, interviews with residents revealed what researchers described as a “metamorphosis of ecosystem services” whereby natural areas valued for recreation came to be seen as vital for survival activities. This phenomenon is dependent upon connection to place built up over time and regular use.

The precedents of the Isle de Jean Charles and Cano Martin Pena demonstrate that communities are the best stewards of their own future. From the concepts of post-disaster metamorphosis of ecosystem services in natural areas and J. B. Jackson’s approach to sense of place, I conclude that connection is inherently a product of time. Pattern, recurrence, and consistency are powerful experiential qualities of landscape that expand our awareness and sustain us in times of turmoil. Punta Santiago is relatively isolated with only one access road. The economic barriers many in Las Parcelas in particular experience increase their vulnerability. The most direct and secure path to higher ground is westward through the reserve which is in need of its own interventions to better manage for habitat diversity and saltwater intrusion. The goal of the design is to propose multi-functional infrastructure that addresses ecological concerns and can support habitation on the coast as long as the community decides to remain in place by serving as an evacuation route. Having not come across documentation of a resiliency plan for Punta Santiago or record of community comment sessions on the subject, the design is intended to facilitate a transition period in the event managed retreat or community relocation come under consideration, by allowing people to use infrastructure they have grown familiar with to continue to access their homes.

The landscape historian J. B. Jackson wrote extensively about the importance of routine and ritual in the formation of sense of place. Localities with a special attraction about them, he posited, “are cherished because they are embedded in the everyday world around us and easily accessible, but at the same time are distinct from that world. A visit to one of them is a small but significant event. We are refreshed and elated each time we are there.” He continued, conveying ideas that have even more weight in the current age of climate change: “In our urban environment which is constantly undergoing irreversible changes, a cyclical sense of time, the regular recurrence of events and celebrations, is what gives us reassurance and a sense of unity and continuity.” These words are apt inspiration for resilient design. The routine interactions we have with infrastructure hold great potential as grounds for creating and maintaining connection.

29 Caño Martin Peña Restoration Project, (Landscape Architecture Foundation), Recording of life webinar.
The vulnerability of Punta Santiago is caused in part by isolation. The community is remote and located in an area of the Puerto Rican coast where hurricanes often make landfall. Additionally, its residents face many social and economic challenges which are magnified by storms and their damage to homes, health, and livelihoods. The landscape of the Delta bears witness to the many forms Punta Santiago has taken to sustain itself through the years. Now, at a time when climate change poses questions of the community’s future on the coast, the oldest way of life in the Delta, fishing, is the core of economic development and supports another growing sector: eco-tourism. Both of these activities rely on the health and beauty of the landscape and their significance to the community represent a deep tie to the coast. The design proposal supports this connection to place, strengthens it by restoring the health of the foundational ecosystems that create it, and seeks to reveal the history of the Delta’s making, all the while serving as a persistent link to home for a coastal community in transition.
Design Overview

The causeway connects Las Parcelas to the coastal hills at the western entrance of Humacao Nature Reserve. Its route links relative high points created by historical infrastructure and past shorelines. Additionally, the causeway functions as an armature for habitat restoration and new recreation programming. The section above shows the sequence of the main elements of the design and their relationship to a Category 5 storm surge and a six foot sea level rise.

6.4 Elevation map of the Delta with the historical shorelines enhanced by the proposed design.
Connect
The existing elevation change along the route of the causeway is 10 feet. In a Category 5 storm, the surge can reach 12 feet in height. At 14 feet, the proposed causeway is safely above the storm surge thereby offering an alternative evacuation route to PR-3, which tends to wash out in storms incurring high maintenance costs for the government and isolating Punta Santiago.

For most of the year, the causeway provides pedestrian and limited vehicular access to the reserve as a park road. Increasing access to the reserve helps residents that visit to fish and hunt, but also creates more attractions for the growing eco-tourism business sector. The layout of the causeway along a historical railroad bed and portions of existing roads, is minimally intrusive to the sensitive habitats in the park.

Restore
Freshwater Swamp and Salt Marsh Habitats

Reveal
Patterns of People in Place

In order to provide for the restored health of these habitats, specifically the Pterocarpus swamp and freshwater wetlands, another important connection made by this design is the reconnection of the river to channelized portions downstream and to its floodplain. I propose dredging a portion of the river channel to re-establish continuous flow into the existing Pterocarpus forest. Additional freshwater input from the reconnected river will help to sustain the swamp against an increase in salinity. Removing vestigial agricultural levees along the river will allow floodwater to flow across the freshwater wetland and contribute fill for the construction of the causeway.
While the earthen berm is an appropriate design for the causeway itself which is intended to persist in its primary function as a road, I wanted to find a more adaptive and resilient solution for water management in the surrounding wetlands.

The remaining freshwater emergent wetlands are not proximal to the lagoons and are sustained by freshwater from rain and runoff. Reconnecting the river to its floodplain allows more freshwater to enter the wetland system. However, since slight changes in elevation significantly effect soil saturation and exposure to brackish waters, it is necessary to buffer the freshwater wetlands from the lagoons and have some ability to modulate water levels. Otherwise emergent wetland vegetation susceptible to saltwater intrusion is easily out-competed by mangroves.

Early in my design process, I explored the idea of a levee system similar to that proposed in the Ecological Assessment and Management Plan from 1997. I was later inspired by the process of sediment trapping in *Pterocarpus* and mangrove roots to design a multi-faceted nature-based system that supports the protection of the freshwater wetlands and the establishment of a *Pterocarpus* restoration planting.
I deployed a system of planting based on the recommendations of the mitigation planting design in which *Pterocarpus* saplings on mounds or ridges to create a buffer between the freshwater wetlands and the brackish lagoon. On the wetland side of the planting, *Pterocarpus* are planted on individual mounds in order to admit flood water into the forest. Remnant canals now carry water to the *Pterocarpus* planting instead of the lagoon, helping to sustain the freshwater swamp species. Of the rows of *Annona glabra* planted to provide shade for the *Pterocarpus*, one is left vacant in order to make a larger channel that can hold higher flood volumes. On the lagoon side of the planting, a ridge and furrow system is used to retain freshwater and break the connection of remnant canals to the lagoons. The creation of a new canal helps improve management of water levels in the adjacent freshwater wetlands which are maintained according to a moist-soil management regime. According to the wetland management plan, impoundments should be drained during the wet season and open grazing. Previously, flood water channeled from the river by remnant canals entered the impoundment and created ponds that disrupted the management schedule. Now, a swale directs water to the new canal by way of the *Pterocarpus* planting. This connection could be modulated with a water control structure such as is used in the second impoundment. It is designed to function in alignment with the seasonal rain patterns by directing excess water through the freshwater forest swamp where it is needed. A notched concrete capped weir located downstream of the channels that connect the *Pterocarpus* forest to the canal, permits kayak access to the lagoons while minimizing the intrusion of brackish water.

The *Pterocarpus* planting became the basis for a series of tree plantings across the site that function to promote habitat diversity and synchronicity with seasonal rain patterns and waterbird use. The species used in the plantings were chosen for their appropriateness to the spectrum of habitats representative of the Delta and sited according to their respective salinity tolerances. *Pterocarpus*, a freshwater swamp species, is planted furthest from the coast in association with freshwater emergent wetland. *Calophyllum brasiliense* (brazil beautyleaf), a species found in the successional coastal forest just beyond the levee, is planted alongside the causeway at the crescent-shaped curve following an old shoreline line. *Annona glabra* (pond apple) is planted in a hemi-marsh fed by stormwater from the community. Finally, the regrowth of the mangrove fringe is encouraged along the existing coastline. For all of these species, siting the plantings on the historical shorelines which are relative high ground in the reserve, offers some protection, from saltwater intrusion as the plantings become established. Additionally, woody vegetation with or without buttress roots, retain soil and prevent sinking that can occur in exposed wetland soils.

*Calophyllum* is salt-tolerant species and a useful native tree for timber. The trees are planted 10 feet on center to optimize timber production and harvesting. Alternatively, the planting can be allowed to thin out and mature to a coastal forest such as what is regenerating in the abandoned palm plantations east of the levee.

The hemi-marsh is a restoration of an area where inundation by brackish lagoon water quickly transitioned wetland from freshwater emergent species to a salt marsh and then a mangrove forest. Freshwater is currently conveyed away from the wetland through the drainage canal and diversion channel. The hemi-marsh was designed to receive stormwater from the community allowing the removal of the culvert that directs precious freshwater out through the diversion channel. The culvert is now located near the other end of the drainage canal which has a subtle slope away from the existing culvert. A new culvert carries water under the levee into the regraded stormwater lagoons. Now, supplied by freshwater, these lagoons can support freshwater vegetation. *Annona glabra* can grow immersed in water, is salt-tolerant, and has phytoremediation capabilities. The plantings act as forebays filtering stormwater when it first enters the system, flowing into the Mandri canal and eventually entering the lagoons. Elsewhere in the reserve, mangroves and other woody species are kept at bay by grazing. This area is less accessible to cattle. Areas that are currently emergent vegetation are generally at or above 2ft of elevation which keeps them above the saturated soils with a higher saline level in which the mangroves thrive. The higher ground is the old shorelines visible in the elevation map of the Delta built up over time, not uniformly, but as mounds. Part of the fill obtained by dredging the stormwater ponds is used to create many distributed mounds to raise up land for emergent vegetation. As a result, more area is returned to hemi-marsh habitat used by waterbirds, especially for mating, nesting, and brood-rearing.
6.7 Proposed plan showing the route of the causeway and the gradient of tree plantings along shorelines past and present.
6.8 Plan of modifications to Rio Anton Ruiz and integration of *Pterocarpus* plantings in improved management of freshwater wetlands.
6.9 Table showing synchronization of climate, habitats, wildlife, and habitat management in the Humacao Nature Reserve.
6.10 Section showing habitat use by resident and migratory waterbirds and fish.

Reveal
The tree plantings and grading projects protect and restore the beautiful and productive landscape that supports many activities important to the coastal community of Punta Santiago. These activities are supported by the causeway itself, a sequence of programming opportunities along its route, and an unfolding narrative of formation of the Delta.

Beginning at the western entrance to the reserve, the Pterocarpus plantings cut across the causeway offering a strong and compelling contrast to the open, expansive emergent wetland views. This is the first suggestion of the pattern of former coastlines enhanced by the design. In this case, the line is a conjecture of the oldest shoreline based off the geometry of the shorelines still legible in the elevation studies of the Delta. Soil building up around the growing trees also means this line is forming anew, over time creating an undulating surface that could help to slow and detain storm surge. A boardwalk trail from the levee follows the canal and leads to a kayak launch near the notched weir and another trail that loops through the forest and along the edge of the lagoon back to the kayak launch. Together the canal and boardwalk trail create a previously inaccessible experience of the Pterocarpus forest via land and water.

Continuing along the causeway, visitors come to a drier and higher forest of Calophyllum planted on a crescent that demarcates another past coastline. The curve straightens out to meet the bed of the old railroad that once transported sugarcane. Upon emerging from this forest, the bridge over the Mandri canal is not far. A pedestrian bridge branches off of the causeway and winds its way underneath where it dips closer to the canal and becomes immersed in the foliage of mangroves. The path
6.11 Section perspective of the moist-soil management area at the western gateway to the Humacao Nature Reserve.

6.12 Section perspective of the *Pterocarpus* swamp and canal.
6.13 Section perspective of *Calophyllum* timber stand on historical coastal crescent.

6.14 Section perspective of hemi-marsh.
lands on an old levee, now shortened and elevated slightly to form a land
dock. At the end of the path is a fishing dock designed in the familiar
form of the Muelle de Punta Santiago. Salvaged trunks from removed
mangroves are placed in the lagoon around another piece of the old
levee for use by birds or boaters looking to set anchor or tie off for a spell.

The causeway continues toward town on the edge of the hemi-marsh. A
second bridge spans the levee and connects with an existing road in Las
 Parcelas that was formerly the path of the railroad into town. Because the
roads in the back of the community are often where stormwater collects,
the causeway continues through a portion of land owned by PECES, a
local non-profit, and intersects PR-3 at its terminus. The causeway is a
bridge through much of this portion because grading an earthen berm
would impact existing homes.

On the other side of PR-3 a pedestrian extension of the causeway
follows the shoreline and ends at the repaired and revitalized Muelle.
As a gathering place and crucial piece of infrastructure for the fishing
community, the Muelle (pier) it was important landmark in Punta
Santiago. Platforms designed to mimic a strand of boats tied together are
nestled in amongst the regenerating mangroves. They offer shaded spots to picnic or take in the beautiful sunrises over the Caribbean Sea. The Muelle, now built of a sturdier construction with concrete pylons, is raised to allow sand to pass underneath helping to alleviate the coastal erosion that occurs south of the Muelle due in part to the pier blocking littoral drift. This design also accommodates sea level rise and allows the pier to be connected to raised boardwalk trail. The end of the dock remains at the existing height and is intended to be submerged over the years and become the substructure for artificial reefs.
6.20 Sections of soil retention over time in Pterocarpus forest

6.19 Transect of Pterocarpus restoration plantings and canal with kayak launch

Pterocarpus officinalis
20’ on center

Annona glabra
20’ on center

Swale

Saltwater Intrusion Measure
Concrete capped notched weir
6.21 Perspective of boardwalk trail in *Pterocarpus* forest.
6.22 Plan of canal bridge and land dock.
6.23 Transect of pedestrian landing off of the canal bridge.

6.24 East elevation of canal bridge and pedestrian landing.

6.25 South elevation of canal bridge and pedestrian landing.
6.26 Plan of restored Muelle de Punta Santiago and boardwalk trail.
6.27 Perspective of restored Muelle and seating along boardwalk trail.
Concluding Thoughts

This thesis was an opportunity to contextualize the impact of the disconnect between disaster relief, disaster recovery, and long-term resilience planning on a specific coastal community. Throughout the process, I endeavored to hold the threads of both societal and landscape change. In doing so, I uncovered a fluid relationship between human intervention and natural processes, and explored a design proposal to align this relationship toward resilience. Landscape architects listen, study, and integrate many voices, views, and possibilities into their work. This thesis demonstrates how these skills uniquely position landscape architects to find synergies between people and ecosystems, in this case through infrastructure that serves a community. The causeway strengthens Punta Santiago, improves managed ecosystems, and provides a conduit to the mainland during disasters.
Bridging the gap between disaster relief, recovery, and resilience planning begins with acknowledging the cyclical nature of these processes. Landscape strategies may not address the most immediate challenges post-disaster, but can contribute to greater resilience which translates into less damage and faster recovery in future storms. Patrick Geddes and J.B. Jackson, a biologist and a landscape historian, both of whom contributed seminal thoughts on landscape connection and society, provided the theoretical foundation for a holistic design that reveals and restores the ecosystems underpinning a community’s sense of place.

Communities and ecosystems in a watershed are functionally linked by their proximity and interconnected waterways. The decision to situate my design proposal in a watershed-based site analysis repositions the resilience concerns of coastal communities, especially isolated and economically disadvantaged ones, as connected to the health of a larger hydrological unit. The causeway makes this connection salient by physically linking the coast and the hills. Throughout my research, I spoke with many people in Punta Santiago who shared their connection and commitment to the landscape be it the lagoons, the coast, or Cayo Santiago. Even as an outsider, the special character of the Delta was apparent to me. This thesis, and the analysis underlying it, proposes linkages between the reserve and the community that have not been fully articulated and explored to date. The design approach also deeply respects the connection of the people of Punta Santiago to their home and seeks to support the community’s autonomy in planning for the future impacts of climate change by promoting the longevity of the Delta landscape.

This project inspired many more lines of inquiry than I was able to address within the scope of a single design proposal. Foremost of those is the idea of a temporary community of disaster relief housing that could transition to permanent housing should Punta Santiago decide to undertake managed retreat. I would consider what the optimum layout would be for this temporary community in order to facilitate disassembly in between storms and permanent settlement over time. There are many innovative housing solutions for disaster shelters, many of which are adaptable and portable, and could become the core of a permanent home. I would also consider how to extend the causeway as a pedestrian and kayak trail further up river and link riparian buffers and patches of emergent forest into a forest reserve all the way to the headwaters of the watershed.
Works Cited

*Unless otherwise noted, all field photography is the work of the author.*

*Maps throughout this book were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™*


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