Assessment of Urban Coastal Wetlands Vulnerability to Hurricanes in Puerto Rico

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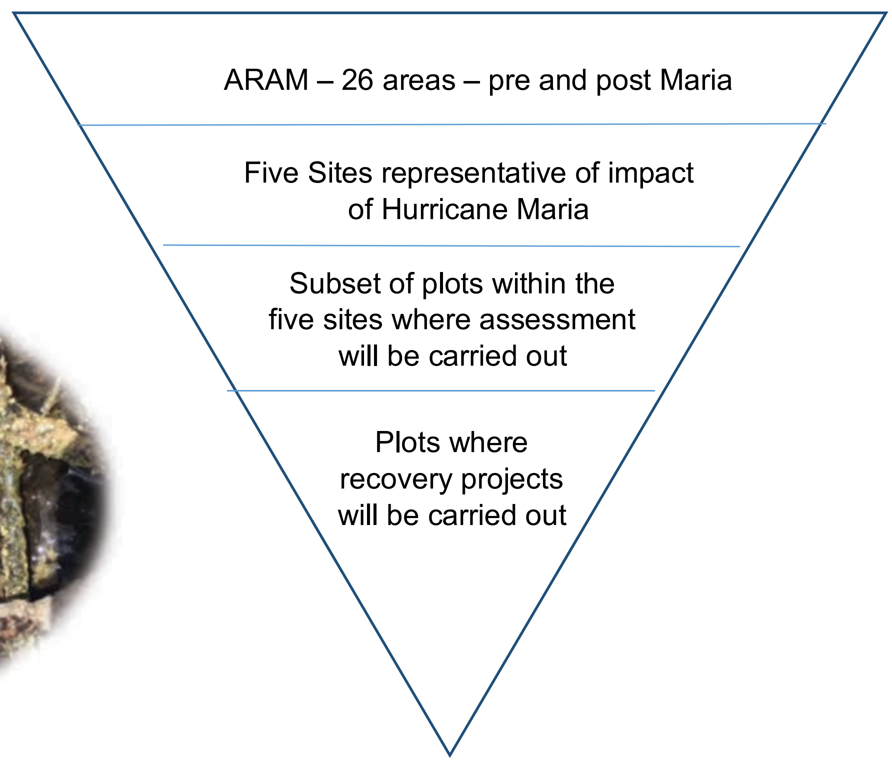

Contents

A. Executive summary

- Hurricanes Irma and María passed over the island of Puerto Rico in September of 2017, resulting in what is widely considered the worst natural disaster in the island's history. Human deaths varied from 64-1052 people. Infrastructure damages range between USD 30-60 billion. It is estimated 23-31 million trees died trees around the island.

- This report presents the results of a rapid assessment of damages at five coastal forested wetland sites near urban or economically important infrastructure across the island. The sites are: Punta Tuna (Maunabo), Punta Santiago (Humacao), Piñones (San Juan), Cienaga Las Cucharillas (Cataño) and Jobos (Isabela).

- To assess the overall changes in vegetation types and mortality, we used spatial imagery datasets from 2010 and 2018 to classify live and dead vegetation from before and after the hurricanes. We also conducted on the ground surveys at three plots within each site, in order to corroborate aerial classifications and to assess the hydrological and geomorphological conditions at each site.

- Findings

    - Primary damage to all sites was in the form of defoliation, uprooting of trees, and or breaking of tree branches and trunks. Damage to vegetation varied greatly across the sites and depending upon habitat type. Overall mortality across all sites and habitats was 27%, overall mangrove mortality was 53%

    - The mangroves at Isabela suffered the most damage, with 95% of the post-hurricane forest classified as dead.

    - The mangroves at Punta Tuna also suffered widespread mortality, with 68% - 98% of mangrove habitat classified as dead.

    - There are shifts in vegetation types in the Ciénaga Las Cucharillas due to a change in the hydrologic regime of the area.

- Course of Action: Isabela- Jobos:
    - Reestablish marine terrestrial connectivity in the wetland for 2019
    - Perform consistent hydrologic monitoring
    - Restore the vegetation by planting mangrove saplings of *Rhizophora mangle*, *Laguncularia racemosa* and *Avicennia germinans* during the 2018-2019
    - Re-assessment of vegetation structure and cover every year
- Course of Action: Punta Tuna – Maunabo

    - Establishment of a memorandum of understanding (MOU) of local managers with USACE, allowing for channel maintenance to be carried out as needed and deemed necessary by local managers
    - Perform consistent hydrologic monitoring
    - Restore the vegetation by planting mangrove saplings in 2018-2019
    - Re-assessment of vegetation structure and cover every year
- Course of Action: Cienaga Las Cucharillas
    - Funding /Repair/ Management improvements at DRNA pump station for 2019
    - Perform consistent hydrologic monitoring
    - Restore 10 ha of wetland by planting mangrove saplings
    - Monitoring of water depth, salinity and flooding
    - Re-assessment of vegetation structure and cover every year
- Course of Action : Punta Santiago
    - Passive monitoring of hydrology and vegetation with no active management
    - Re-assessment of vegetation structure and cover every year
- Course of Action – Piñones
    - Passive monitoring of hydrology and vegetation with no active management
    - Re-assessment of vegetation structure and cover every year

- Total Costs for the implementation of all courses of action at all sites is estimated at $12,025,00

B. Background and Purpose

Hurricanes Irma and María passed over the island of Puerto Rico in September of 2017, resulting in what is widely considered the worst natural disaster in the island's history. The number of human deaths from the storms has been widely debated and is thought to be between 64 and 1052. Most of the deaths following the storm resulted from medical complications because of crippled power and health system infrastructure due to one of the largest blackouts in history. This infrastructure was primarily impacted by category five storm force winds, flying debris, as well as extensive and prolonged flooding from precipitation, storm surge, and failed hydraulic infrastructure. Current estimates of damages range between USD 30 and USD 60 billion and will require years of extensive repairs. Damages to natural resources are less well understood but preliminary estimates suggest the loss of around 23-31 million trees across the island. Previous weather or tsunami disasters have shown coastal wetlands to provide significant protection to human life, property, and infrastructure to the order of USD 33,000 per hectare. This report presents the results of a rapid assessment of damages at five coastal forested wetland sites near urban or economically important infrastructure across the island. It then recommends potential rehabilitation actions to rehabilitate the functional and protective capacity of these wetlands to pre-storm levels. Previous studies of hurricane regeneration after hurricanes or similar disturbances suggest 100% recovery to take around 30 years (Ferwerda et al., 2007). However, this timeframe is likely to be significantly extended in the absence of viable seeds, which may be the case in sites where hydrology has been drastically altered.

Coastal wetlands depend on and are affected by both terrestrial/marine and marine/ terrestrial connectivity in which both human activity and natural processes, such as hurricanes and storm events, play an important role. Forested coastal wetlands have been singled out as providing extremely highly valuable protective services against natural disasters (Mazda et al., 1997; Othman, 1994). Thus, by maintaining this service via rehabilitation and the enforcement of established federal and state regulations, these ecosystems would contribute to the goal of increasing the resilience of Puerto Rico's coast against similar natural disasters. As is the case in the other sites, hydrology must be the focus of any intended rehabilitation program.

The purpose of this assessment is to provide recommendations towards the restoration of the resiliency and functional capacity of Puerto Rico's coastal wetlands (hydrology and vegetation structure) to act as a natural barrier vital to reduce or minimize the eminent threats to lives and livelihoods, public infrastructure security and human health. We assessed the changes in mangrove and coastal wetland hydrology and functional habitat coverage after hurricanes Irma and María at five sites across Puerto Rico, based on their relative potential to reduce or minimize eminent threats to lives and livelihoods, public infrastructure, security, human health and tourism. This was done by comparing pre-storm information when available to information gained from a post-storm assessment carried out at all five sites during the month of April 2018. This included spatial imagery and elevation datasets as well as on-site assessments of hydrology, geomorphology, tree mortality, and water chemistry. With this information we were able to determine mortality and damage extent as well as likely causal factors.

C. Site Selection

Five sites across the island were chosen for their relative potential to reduce or minimize eminent threats to lives and livelihoods, public infrastructure, security, human health and tourism (Figure 1). This was determined based on results the Antilles Rapid Assessment Methodology carried out after the hurricanes (Appendix C). Additional input from local experts in the Puerto Rico Department of Natural Resources, the United States Army Corps of Engineers, and The University of Puerto Rico was also considered. Of the five sites, two were in the metropolitan area of Carolina-San Juan-Cataño in the northern coast, two sites were in the eastern and south eastern coast of the island, and one in the northwestern side of the island. The two sites in the San Juan metropolitan area are representative of urban coastal wetlands surrounded by high population density, and transportation and industrial infrastructure. On the eastern end, Piñones State Forest is primarily woody vegetation habitat dominated by mangroves. This site is within 3.5 km of the island's busiest international airport and is also an important component of both internal and external tourism. On the western side, Ciénaga Las Cucharillas is composed of both woody and herbaceous vegetation and is within 4 km of the shipping and port related industries of the san Juan Bay. The Ciénaga is an important component of local hydrology and the maintenance of low flooding conditions in the surrounding areas composed of high population density neighborhoods, and transportation and industrial infrastructure. One hundred kilometers to the west, the mangroves of Isabela are near where Hurricane María left the island and are of high economic importance to internal and external tourism. On the southern coast, Punta Santiago lies between the ocean and the town of Humacao, near where hurricane María made landfall. This site is composed primarily of both upland forests as well as saltwater forested wetlands. Finally, Punta Tuna lies roughly twenty-five kilometers southwest of Punta Santiago and is composed of both woody and herbaceous marine and freshwater wetlands, as well as upland forests.

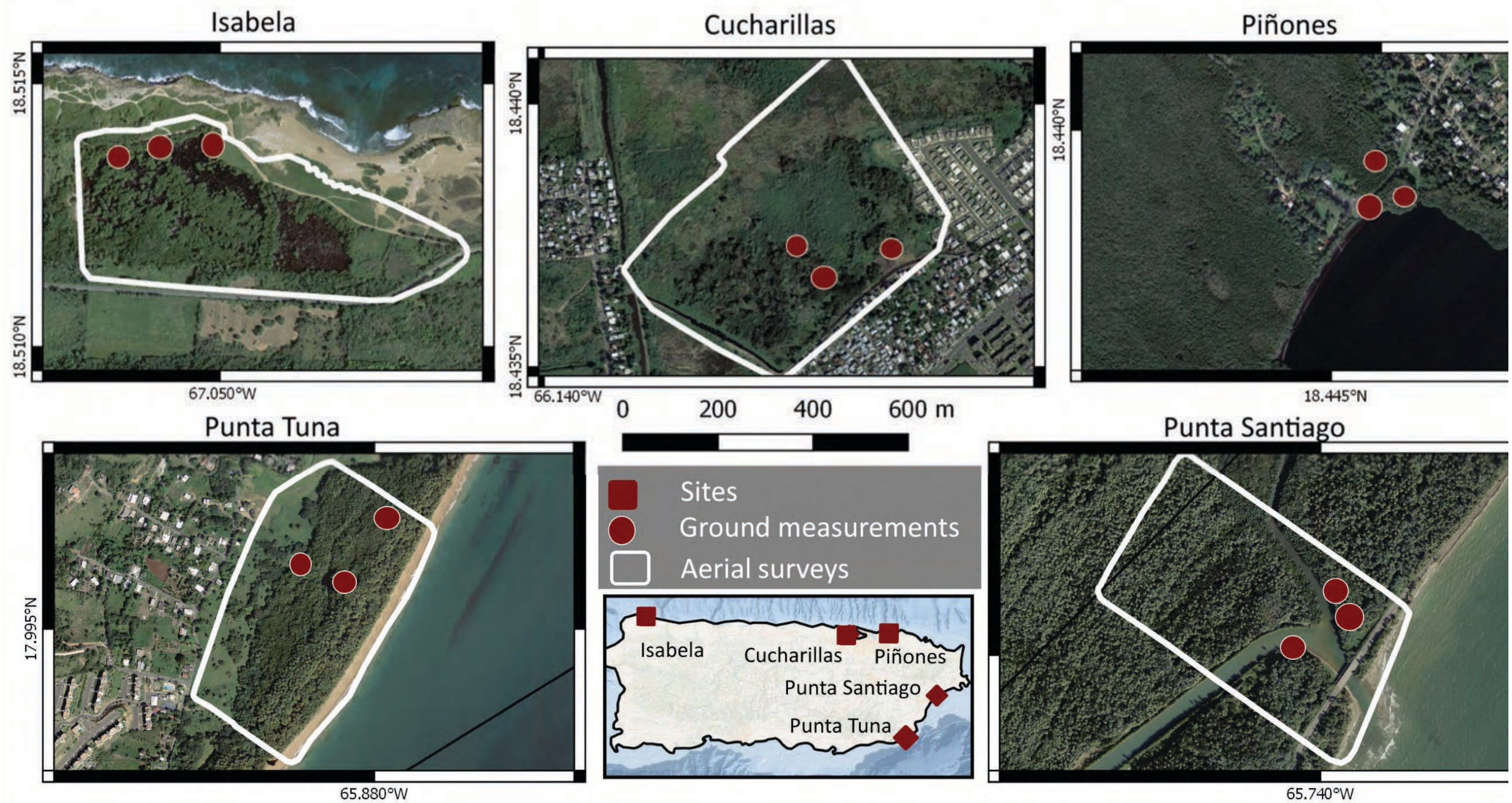

Figure 1 Rapid assessment sites for coastal wetlands. Five sites were chosen based on expert input and the economic and infrastructural importance of the sites. Isabela represents hurricane María's exit from the island. Cucharillas and Piñones represent the island's largest urban and industrial center. Punta Santiago and Punta Tuna represent where the hurricane made landfall and the nearby city of Humacao. Distance bar applies to all insets except the island wide center map. Imagery is pre-hurricane from 2010. White polygons represent aerial survey boundaries. Piñones was not assessed by air due to restrictions from the nearby international airport.

D. Changes in Mangrove and Coastal Wetland Mortality at Five Sites in Puerto Rico

Methods

To assess the overall changes in vegetation types and mortality, we used a series of spatial imagery datasets from 2010 and 2018 along with spatial geoprocessing software to classify live and dead vegetation from before and after the hurricanes. Habitat types were taken from a pre-classified spatial datasets of coastal wetland habitat classes from 2010 (Office for Coastal Management, 2017). Live and dead vegetation within the various wetland groups was then determined from aerial imagery from 2010 (OCM Partners, 2018) and 2018 (this assessment). Pre-hurricane aerial imagery was obtained from island wide coverage from the flights organized by the United States Army Corps of Engineers in 2010. Post-hurricane imagery was obtained from a small unmanned aerial vehicle (UAV) flown over specific sites in April 2018 (this study). These images were classified into live and dead vegetation, as well as bare ground and open water using a series of pixel training and classification processes in spatial geoprocessing software. As part of this process, we first outlined areas in the images and assigned them to one of the four categories: 1) live vegetation, 2) dead vegetation, 3) water, or 4) bare ground. The software then uses these training areas in a random forest statistical decision process to categorize the remaining pictures in the image based on their similarity to the training areas. The resulting classified pixels were summed per habitat class and tables were produced for each habitat and its resulting classification as alive, dead, water or ground. The methodology assumes that any vegetation without foliage eight months after the hurricane is dead. For the site at Piñones, post-hurricane aerial imagery was not available due to the restrictions in flying the UAV in proximity to the Luis Muñoz Marín International airport.

We also conducted on the ground surveys at three plots within each site, in order to corroborate aerial classifications and to assess the hydrological conditions at each site. The plots were five-meter radius circles where the following vegetation measurements were made: a) number of live trees, b) number of dead trees, c) percentage of trees as mangroves, d) percentage coverage as forest, e) percentage of coverage as herbaceous, f) number of live mangrove pneumatophores (aerial roots, important for gas exchange), and g) number of seedlings. Water chemistry measurements were taken with a Hydrolab multimeter sonde and consisted of temperature, pH, salinity, specific conductivity, and dissolved oxygen. Finally, we installed water level recorders at some of the sites where modifications to the hydrological conditions were detected. These recorders measured water depth every half of an hour and were installed from two weeks to two months depending upon the site. Two specialists from the Natural Resources Conservation Service also visited the sites with us to assess hydrology and geomorphology. We have incorporated important components of their assessment in our report and the complete assessment is included as Appendix D.

Results

Damage to vegetation varied greatly across the sites and depending upon habitat type (Figures 2,5,7,9, Tables 1-4). Below is a list of overall findings followed by site specific results at each location:

a) Overall mortality across all sites and habitats was 27%, but overall mangrove mortality was double at 53%. This corresponds to a total mangrove loss of 15 hectares across the five study sites.
b) The mangroves at Isabela suffered the most damage, with 95% of the post-hurricane forest classified as dead, leaving only a small strip surrounding the wetland shoreline.
c) The mangroves at Punta Tuna also suffered widespread mortality, with 68% of mangrove habitat classified as dead. This is likely an underestimate, as some of the mangrove classified habitat is upland vegetation, which fared better. Ground based observations estimate the mortality at Punta Tuna is closer to 95%. Below are specific results from each site.
d) There are shifts in vegetation types in the Ciénaga Las Cucharillas due to the excess and continuous freshwater flooding as a result of management of flood gates and water pumps at the mouth of the Malaria Channel, where the flood gates have remained closed during the last six years. Failure of the water pumps occurred during and after the hurricane and currently only one is active for half an hour three times daily.
e) The other two sites experience relatively minimal mortality and are expected to recover naturally

Jobos - Isabela

Aerial surveys at Isabela show the most extensive mortality of all sites (Figure 2, Table 1). Across all habitats, 67% of coverage is either dead or converted to bare ground, corresponding to a loss of 13 hectares of live vegetation habitat. Mangrove habitat suffered the highest mortality rate, with 95% dead.

On site assessments at Isabela confirmed almost complete mortality, with the only surviving individuals present along higher grounds along the shore of the wetland (Figure 3). When measuring water depth just inside the wetland, it was discovered that numerous black mangrove pneumatophores (aerial roots) were submerged. These roots are extremely important for mangrove survival, serving as a conduit for air to reach often flooded root zones and thus allowing for normal plant metabolism. These roots will grow to a height just above normal flood depth, allowing for gas exchange with the air even when flooded. The fact that these roots were flooded and that the only surviving trees were found along higher shorelines, provides strong evidence that extremely high and prolonged flooding as a result of the hurricanes effectively drowned the trees and resulted in their death. Water depth recordings at the site (Figure 3), further confirm this in that they show no tidal connectivity and very slow drainage or evaporation. The hydrological and geomorphological assessment (Appendix D) suggests the bike path constructed along the wetland perimeter may be impeding normal tidal connectivity and this may have worsened as a result of the deposition of sand during the storm. Water chemistry measurements were normal for mangrove wetlands and are not thought to be the cause for mortality (Appendix B).

Course of Action:

Given that abnormally high and prolonged flooding as a primary cause of wetland mortality, and in accordance with the NRCS hydrology assessment, we recommend:

1) Reestablish wetland connectivity with the ocean for 2019. This includes the construction of a tidal channel as well as improvements and maintenance to existing infrastructure (bike path and flow channels under the bike path.
2) Perform consistent hydrologic monitoring to ensure the establishment of sustainable hydrology in parallel with vegetation rehabilitation.
3) Restore the vegetation by planting mangrove saplings of *Rhizophora mangle*, *Laguncularia racemosa* and *Avicennia germinans* in 2018-2019, so that a full forest can develop within the next ten years. Without planting, natural regeneration to a full forest will occur from existing reproductive trees, although this is likely to take twenty to thirty years. However, with or without planting, any regeneration will be impeded and vulnerable if the geomorphological and hydrological conditions are not improved.
4) Re-assessment of vegetation structure and cover every year by on the ground measurements of seedling and tree density and canopy cover and at the landscape level utilizing un-manned aerial vehicles.

Isabela, Puerto Rico

2010 **2018**

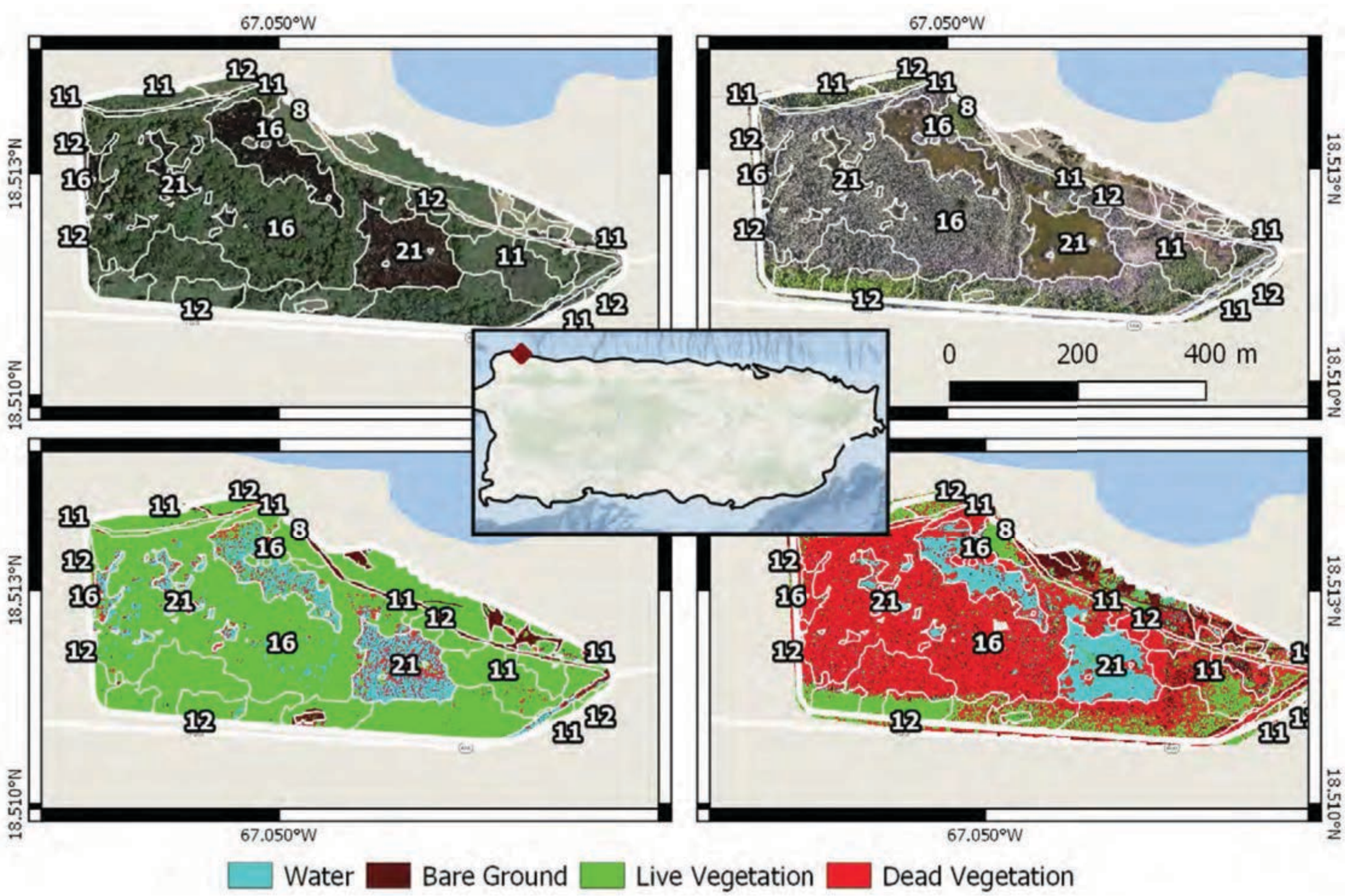

Figure 2 Aerial imagery of the mangroves at Isabela, Puerto Rico from 2010 to 2018, representing pre and post hurricane, respectively. Numbers represent major habitat classes as represented in the below table. Isabela suffered the highest mangrove mortality rate of all sites. Surviving mangroves were concentrated on higher elevations shorelines, suggesting mortality was due to higher than normal water levels for longer than normal duration. Habitat class 21 is open water. Recovery of mangroves at Isabela would benefit from active management.

			2010				2018			
	Habitat Type	Area (ha)	Water	Bare Ground	Alive Veg.	Dead Veg.	Water	Bare Ground	Alive Veg.	Dead Veg.
8	Grassland/Herbaceous	2.4	1%	6%	93%	0%	3%	42%	27%	28%
11	Upland Forest	4.7	1%	1%	97%	1%	0%	6%	33%	61%
12	Scrub/Shrub	2.9	1%	2%	94%	2%	0%	6%	56%	37%
16	Estuarine Forested Wetland	7.5	6%	0%	91%	3%	3%	0%	2%	95%

Table 1 The mangroves at Isabela suffered the highest mortality rate of all included sites, with aerial imagery suggesting 95% mortality, equivalent to nearly 7.5 hectares of forest. Other vegetation also suffered to a lesser extent.

Figure 3 While most of the mangroves at Isabela are dead (left), there are some live trees and seedlings along the higher grounds on wetland shore (right).

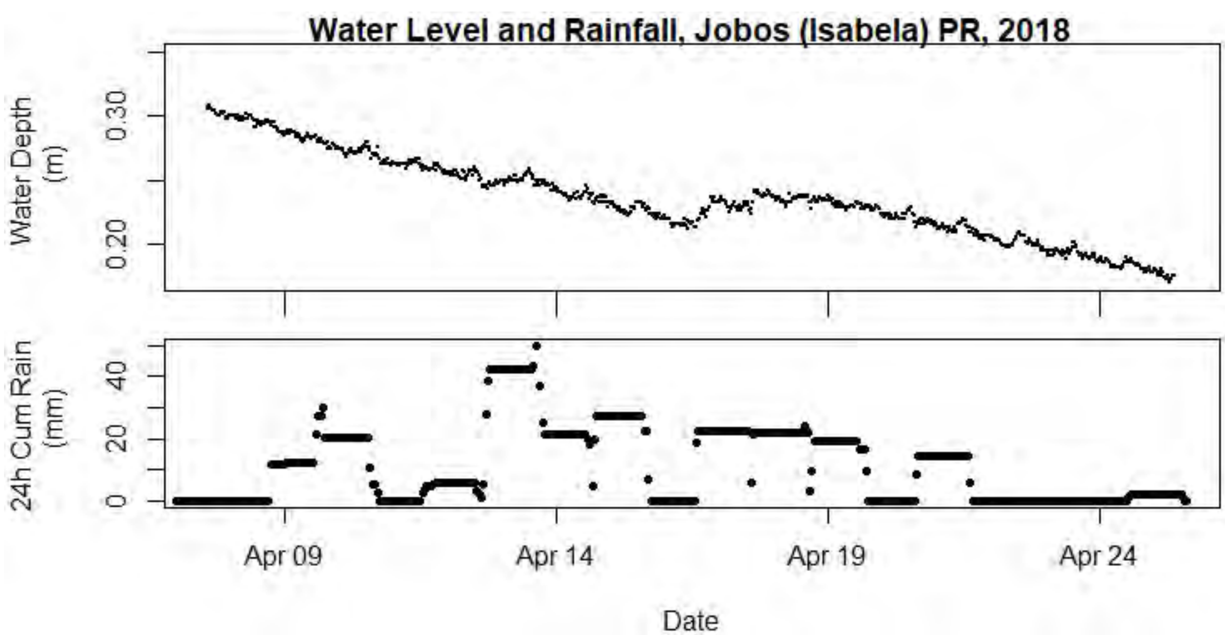

Figure 4 Water levels recorded at Isabela mangroves, Puerto Rico over a two-and-a-half-week period show a reduction of ten centimeters, with some response to local rainfall, and no tidal signature. This suggests the wetland is almost completely dependent on rainfall and thus vulnerable to extreme events like hurricanes. Better drainage would have allowed flood waters to recede quicker and would provide improved tidal connectivity.

Punta Tuna

Punta Tuna suffered similar mortality to that of Isabela (Figure 5, Table 2). Aerial surveys suggest an overall mortality of 29%, but mangrove mortality was more than double at 68%, and on-the-ground surveys suggest a much higher mortality closer to 95%. The reason for the discrepancy is the misclassification of upland forest as mangrove habitat in the habitat classification dataset (Office for Coastal Management, 2017). Overall, eight hectares of mangrove died within the study area.

On site assessment at Punta Tuna showed similar patterns of mortality as that of Isabela, with only a small ring of surviving forested wetland along the higher ground perimeter. We again suspect the same process of events as that of Isabela leading up to the mass mortality. Local managers confirmed the normal drainage creek at Punta Tuna was blocked by sand deposition during hurricane María. With the accumulation of extreme precipitation and no means of drainage, the trees were drowned following prolonged flooding. Flood lines on trees suggest the water level was sustained at around 70 cm of depth for up to four months, which is too high to allow for oxygen exchange with roots (Figure 6). Water level recordings at the site confirmed no tidal connectivity and a strong dependence on rainfall. This makes the wetland especially vulnerable to extreme flooding and mortality following heavy rainfall events. Water chemistry parameters showed no abnormalities (Appendix B).

Course of Action:

Hydrology was the primary cause of mortality at Punta Tuna and should thus be the focus of any rehabilitation program. Maintaining a consistent and sustainable connection with the ocean will allow for proper drainage in the case of extreme flooding as well as provide the tidal connectivity necessary for long term mangrove health.

1) The NRCS assessment (Appendix D) recommends ensuring proper communication with USACE and the establishment of a memorandum of understanding (MOU) allowing for channel maintenance to be carried out as needed and deemed necessary by local managers. Only by first ensuring stable and proper hydrology, can vegetative rehabilitation be successful.
2) Perform consistent hydrologic monitoring to ensure the establishment of sustainable hydrology in parallel with vegetative rehabilitation.
3) Implementation of an active management plan that includes planting of mangrove saplings to restore 100% mangrove cover and structure.
4) Re-assessment of vegetation structure and cover every year by on the ground measurements of seedling and tree density and canopy cover and at the landscape level utilizing un-manned aerial vehicles.

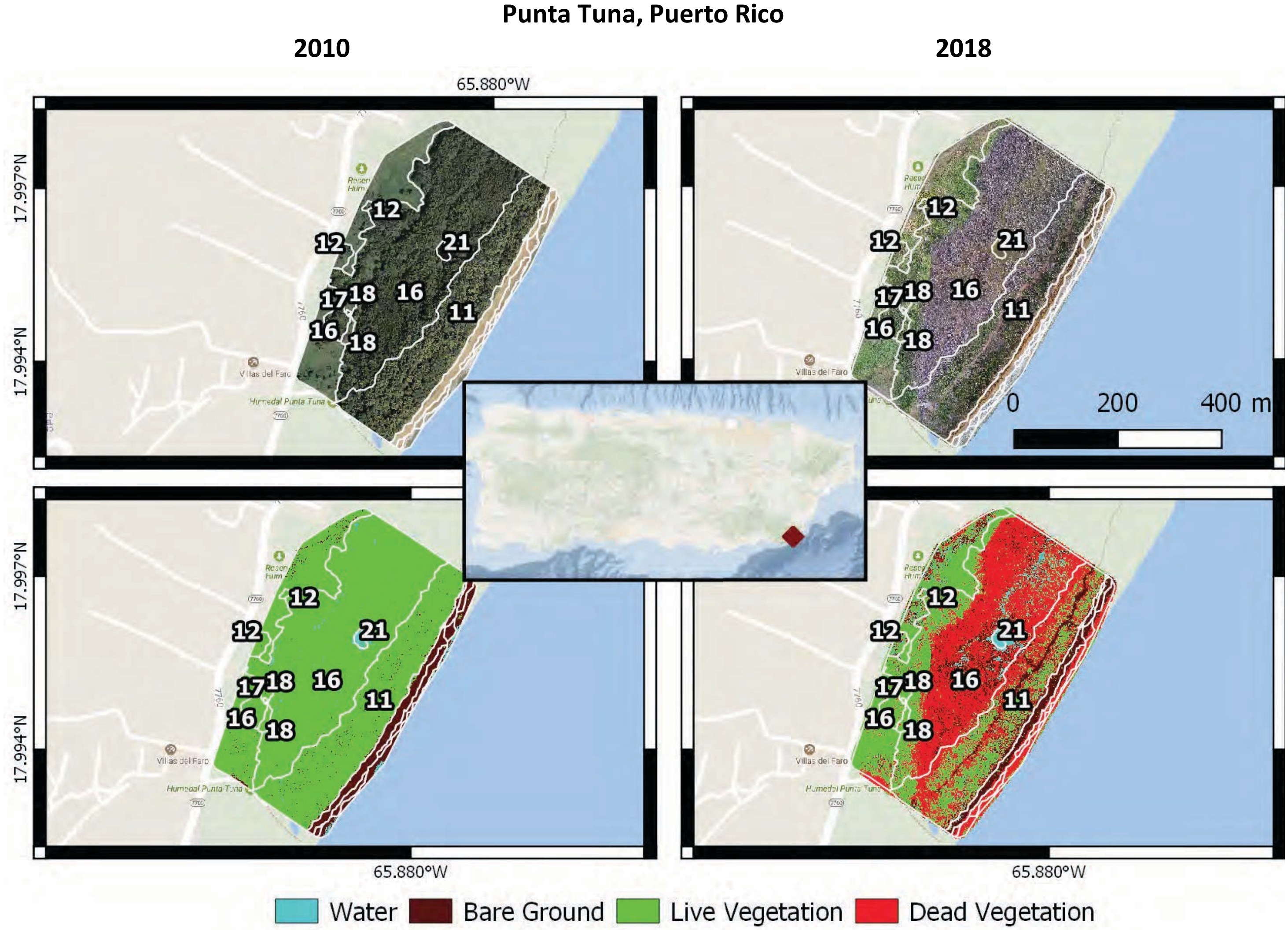

Figure 5 Aerial imagery of the mangroves at Punta Tuna, Puerto Rico from 2010 to 2018, representing pre and post hurricane, respectively. Numbers represent major habitat classes as represented in the below table. Punta Tuna suffered among the highest mangrove mortality rates of all sites. Punta Tuna is not expected to recover naturally within the next decade and would benefit significantly from active management.

			2010				2018			
	Habitat Type	Area (ha)	Water	Bare Ground	Alive Veg.	Dead Veg.	Water	Bare Ground	Alive Veg.	Dead Veg.
11	Upland Forest	4.9	0%	2%	99%	0%	0%	15%	40%	44%
12	Scrub/Shrub	0.1	0%	0%	100%	0%	2%	7%	88%	3%
16	Estuarine Forested Wetland	8.8	1%	0%	99%	0%	4%	4%	23%	68%
18	Estuarine Emergent Wetland	0.1	0%	0%	100%	0%	0%	0%	100%	0%

Table 2 The mangroves at Punta Tuna suffered high mortality, with aerial imagery suggesting 68% mortality, equivalent to nearly 6 hectares of forest. Other vegetation also suffered to a lesser extent.

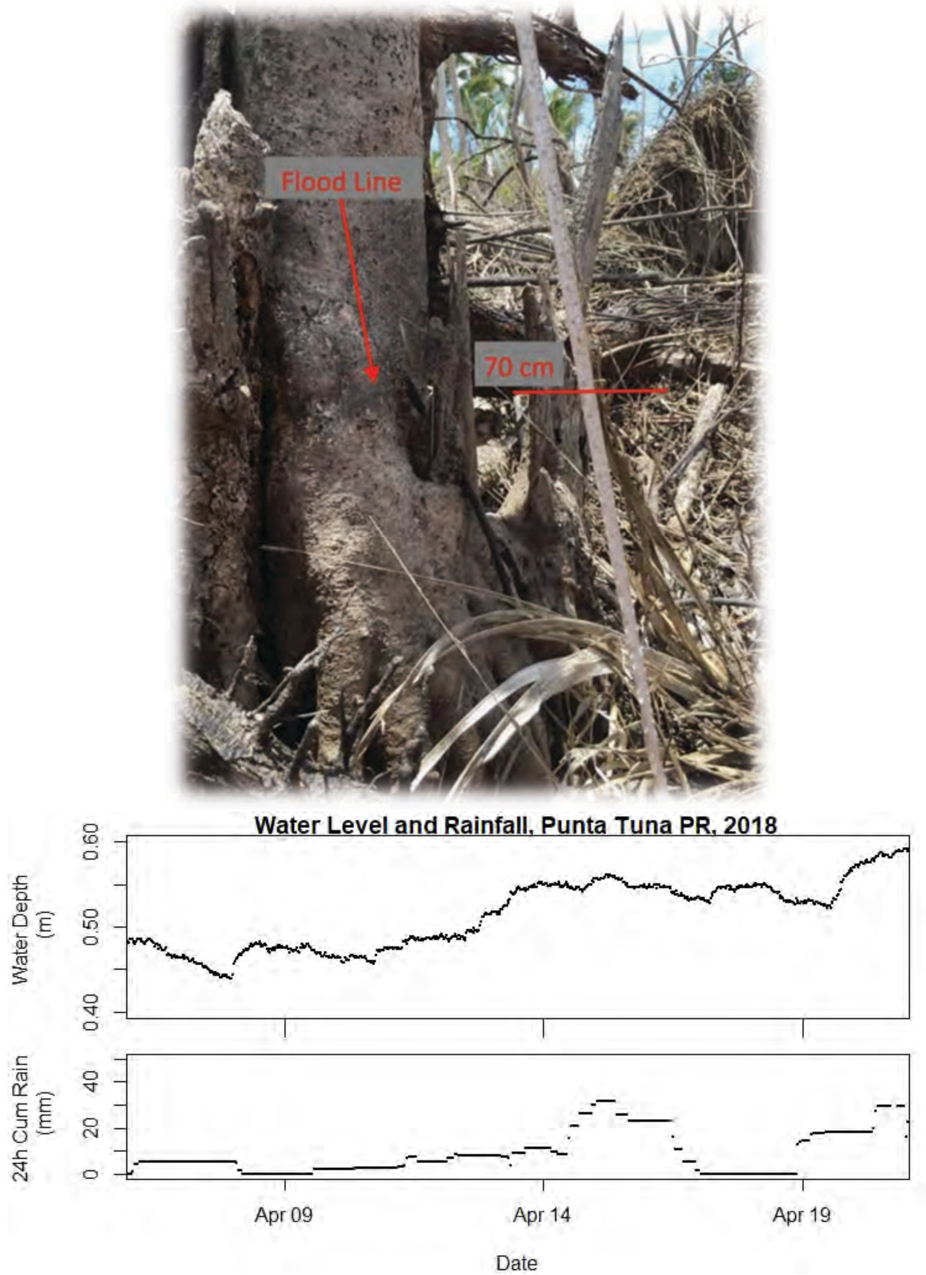

Figure 6 Flood lines on trees at Punta Tuna suggest a sustained water level of 70 cm above the forest floor and locals suggest the wetland was flooded for up to four months (top). These flood waters did not allow for proper oxygen levels in mangrove roots, and effectively drowned them. Water levels recorded at the site show minimal tidal signals and no drainage, with a strong connection to rainfall (bottom). This leaves the wetland vulnerable to flooding from extreme events like hurricanes.

Ciénaga Las Cucharillas

Initial damage and flooding in Ciénaga las Cucharillas was extensive (Figure 7). Ciénaga las Cucharillas contains the highest diversity of wetland habitats relative to the other sites, all of which suffered some mortality as well as significant shifts towards other habitats (Figure 8, Table 3).

Figure 7 Aerial view of Ciénaga Las Cucharillas and surrounding urban and industrial infrastructure immediately after hurricane Maria. Photo Date: 9/23/2017 8:42:33 AM http://imageryuploader.geoplatform.gov/imageeventspublic/map.html#

Even if there was initial extensive defoliation and breakage, the site experienced 6% mortality with the highest rates around 14% seen in palustrine (freshwater) emergent wetlands and estuarine (saline) forested wetlands. Viable White mangrove (*Laguncularia racemosa)* seedlings and saplings were observed at the site, suggesting natural regeneration. However, 16% and 8% of palustrine emergent and estuarine forested wetlands, respectively, were also converted to open ground. Additionally, some small sections of bare ground have been colonized by grasslands. These trends signify shifting vegetation habitats that might be in response to altered hydrology from the management of the flood gates and pumps after the hurricane. Altogether, this site lost around 1.6 hectares of vegetated habitat with significant changes in vegetation, from wooded vegetation to freshwater grasses and sedges.

Although Ciénaga Las Cucharillas suffered relatively little mortality in comparison to other sites, its shifting vegetation is a sign of potential habitat conversion at the site.

Ciénaga las Cucharillas, Puerto Rico

2010 **2018**

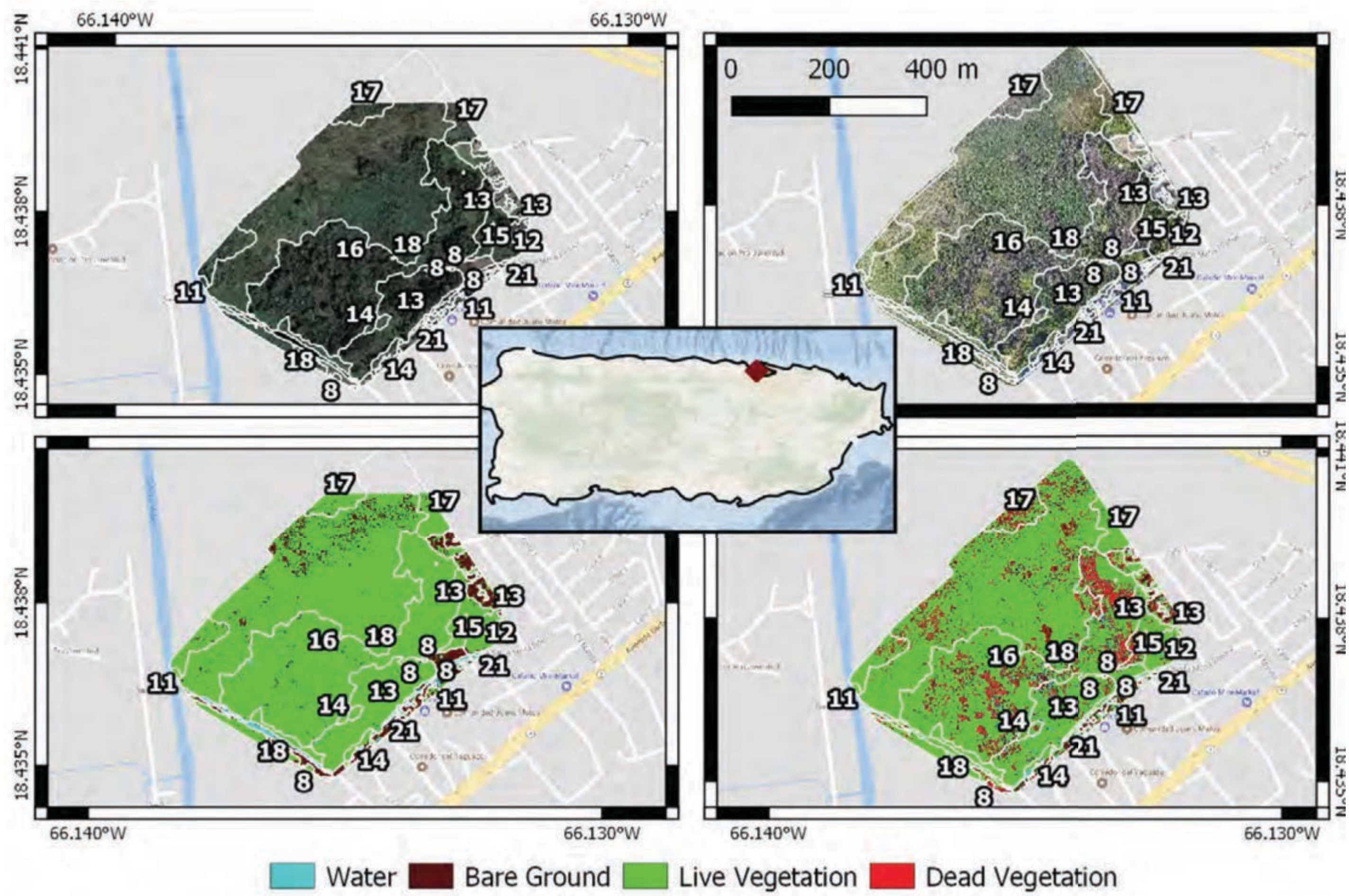

Figure 8 Aerial imagery of the mangroves at Cataño, Puerto Rico from 2010 to 2018, representing pre and post hurricane, respectively. Numbers represent major habitat classes as represented in the below table. Cataño suffered moderate mortality compared to other sites.

			2010				2018			
	Habitat Type	Area (ha)	Water	Bare Ground	Alive Veg.	Dead Veg.	Water	Bare Ground	Alive Veg.	Dead Veg.
8	Grassland/Herbaceous	0.3	0%	65%	35%	0%	0%	2%	91%	6%
11	Upland Forest	0.2	17%	36%	48%	0%	14%	36%	48%	2%
12	Scrub/Shrub	0.1	0%	6%	94%	0%	0%	5%	93%	1%
13	Palustrine Forested Wetland	2.9	1%	3%	96%	0%	4%	6%	85%	5%
15	Palustrine Emergent Wetland	0.4	10%	7%	83%	0%	8%	16%	63%	14%
16	Estuarine Forested Wetland	7.6	1%	1%	98%	0%	1%	8%	78%	13%
18	Estuarine Emergent Wetland	10.2	0%	5%	95%	0%	0%	4%	93%	3%

Table 3 The mangroves at Ciénaga Cucharillas suffered moderate mortality, with aerial imagery suggesting 13% mortality, equivalent to nearly 1 hectares of forest. Other vegetation also suffered to a similar or lesser extent.

This is due to a change in hydrology, as has been observed in other coastal wetlands with gradual or rapid changes to hydrology (Ball, 1980; Clark and Csiro, 1988). Our assessment based on water depth and salinity measurements for the last four years by the University of Puerto Rico where marine-terrestrial connectivity is maintained by subsurface inflow of the marine water from the coast, as well as that of the report of NRCS hydrology/geomorphology team, see the pump/gate station at the Malaria Channel as a critical component of site hydrology, and thus to rehabilitating site vegetation to provide optimal protective services (Figure 9). This primarily means allowing sufficient tidal exchange in the wetland to promote its natural estuarine (saltwater) and not palustrine (freshwater) conditions. In doing so, the hydrology will naturally favor a forested wetland system over the current herbaceous dominated system. Forested coastal wetlands have been singled out as providing extremely highly valuable protective services against natural disasters (Mazda et al., 1997; Othman, 1994), thus maintaining via rehabilitation and enforcement of established federal and state regulations, these ecosystems would contribute to the goal of increasing the resilience of Puerto Rico's coast against similar natural disasters. As is the case in the other sites, hydrology must be the focus of any intended rehabilitation program. Parallel to establishing a favorable hydrological, vegetative rehabilitation with mangrove plantings need to be carried out for optimal success.

Figure 9 some of the mortality at Ciénaga Cucharillas (left) is likely a result of shifting hydrology due to the pump/gate station at the mouth of the Malaria canal (right). A freshwater hydrology regime is promoted by the operation of the tidal gate at the mouth of the Malaria Channel managed by the Department of Natural Resources and Environment (DRNA), where for the past six years the flood gates have not been opened, restraining the marine-terrestrial connectivity through the channel and favoring freshwater conditions in the area.

Course of Action:

Parallel to establishing a favorable hydrological, vegetative rehabilitation with mangrove plantings need to be carried out for optimal success.

1) Funding /Repair/ Management improvements at pump station/ tide gates to be carried out by 2019 for reestablishing marine -terrestrial connectivity and prevention of flooding episodes.
2) Planting of ten ha with Black mangrove and White mangrove saplings by 2020 to cover and structure.
3) Monitoring of water depth, salinity and flooding.
4) Re-assessment of vegetation structure and cover every year by on the ground measurements of seedling and tree density and canopy cover and at the landscape level utilizing un-manned aerial vehicles.

Punta Santiago

The mangroves at Punta Santiago suffered primarily wind damage, with little evidence for drastically altered hydrology. Overall mortality at Punta Santiago was 34%, with most of the loss occurring in upland forests, not wetlands (Figure 11, Table 4). Wetlands experienced a loss of 34%, corresponding to a loss of around 1.6 hectares. Viable seeds were observed at the sites, suggesting natural regeneration will occur, and no abnormalities in water chemistry were measured. Further, the NRCS hydrology/geomorphology report found no significant alterations to site hydrology. This suggests the primary damage to the vegetation at Punta Santiago was due to wind and that no active management is necessary for rehabilitation. We therefore recommend a passive monitoring program with no active management unless significant changes in recovery are detected.

Figure 10 The mangroves at Punta Santiago suffered a mortality rate of 34%, although natural regeneration, including seed germination and tree re-sprouting has already begun. Recommendations are to passively monitor and allow for natural regeneration.

Course of Action:

1) Passive monitoring program with no active management unless significant changes in recovery are detected.
2) Re-assessment of vegetation structure and cover every year by on the ground measurements of seedling and tree density and canopy cover and at the landscape level utilizing un-manned aerial vehicles.

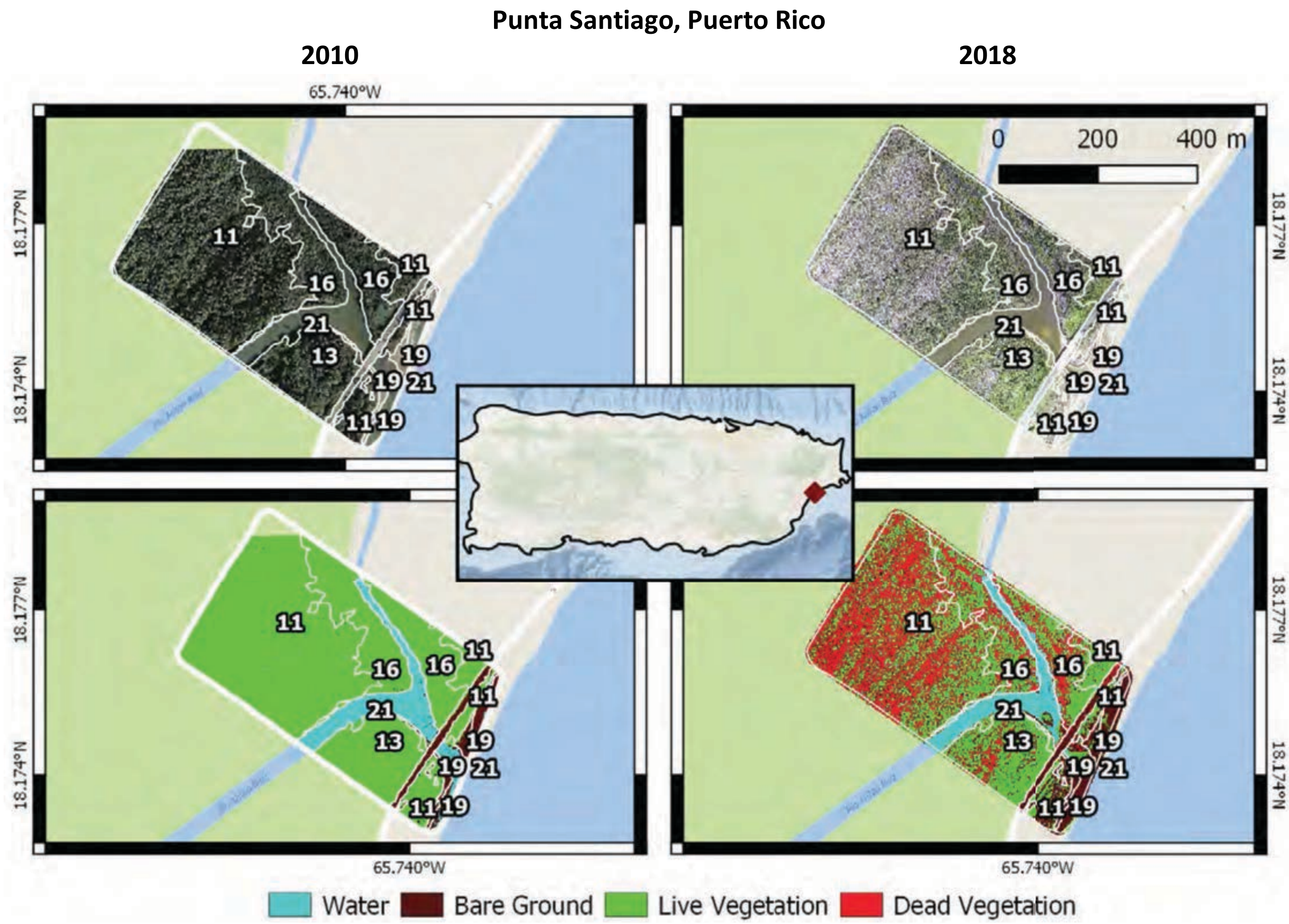

Figure 11 Aerial imagery of the mangroves at Punta Santiago, Puerto Rico from 2010 to 2018, representing pre and post hurricane, respectively. Numbers represent major habitat classes as represented in the below table. Punta Santiago suffered moderate mangrove mortality rates and is expected to recuperate naturally and would not likely benefit significantly from active management.

			2010				2018			
	Habitat Type	Area (ha)	Water	Bare Ground	Alive Veg.	Dead Veg.	Water	Bare Ground	Alive Veg.	Dead Veg.
11	Upland Forest	10.9	0%	1%	99%	0%	0%	8%	45%	47%
12	Scrub/Shrub	2.5	1%	0%	99%	0%	0%	7%	83%	10%
16	Estuarine Forested Wetland	4.5	3%	0%	97%	0%	7%	2%	57%	34%

Table 4 The mangroves at Punta Santiago suffered moderate mortality, with aerial imagery suggesting 34% mortality, equivalent to nearly 1.5 hectares of forest. Other vegetation also suffered to a greater extent, such as upland forests.

Piñones

Although no aerial surveys were possible at Piñones due to restrictions from the nearby international airport, we were able to assess the site on the ground (Appendix B). This assessment found 30% mortality in the mangroves, with sufficient live mangrove seedlings and hydrological and water chemistry conditions that did not suggest any imminent threats to ecosystem vitality (Figure 12). We expect natural regeneration and canopy closure to occur over the next five years. Therefore, we recommend only passive monitoring to ensure natural rehabilitation occurs unimpeded and no active vegetation rehabilitation unless significant changes are detected.

Figure 12 The mangroves at Piñones suffered a mortality rate of 30%, although natural regeneration, including seed germination and tree re-sprouting has already begun. Recommendations are to passively monitor and allow for natural regeneration.

Course of Action:

1) Passive monitoring program with no active management unless significant changes in recovery are detected.
2) Re-assessment of vegetation structure and cover every year by on the ground measurements of seedling and tree density and canopy cover and at the landscape level utilizing un-manned aerial vehicles.

E. Discussion

Primary damage to all sites was in the form of defoliation, uprooting of trees, and or breaking of tree branches and trunks. While destructive to individual trees, these forms of damage do not typically result in forest wide mortality (Doyle et al., 1995; Roth, 1992). This was evident in the moderate mortality rates observed at three of the five sites, where less than fifty percent of mangrove coverage was classified as dead. In these cases, it is expected the surviving trees will be capable of reaching near full canopy coverage in the next 12-18 months. Further, with some viable germinating seeds and seedlings present at these sites, understory coverage has already begun to regrow and will continue to fill in remaining canopy gaps. We expect these sites to reach pre-hurricane forest metrics of stem density and diameter over the next five years (Baldwin et al., 2001). Complete secondary succession of large patches may take longer, around 15 years, but only if the appropriate hydrology is maintained and if there is a sustainable supply of germinated seeds from adjacent stands (Cintrón-Molero, 1992; Watson, 1928). The two sites at Punta Tuna and Isabela, however, do not meet these criteria and will require active management towards an accelerated recovery.

Unlike the primarily wind damage at the other sites, the mangroves of Punta Tuna and Isabela were likely affected by drastic changes in hydrology (Lugo et al., 1981). At Punta Tuna, the closing of the wetland channel by sand deposition during the storm, followed by the flooding from precipitation and storm surge, resulted in extremely high-water levels and no drainage channel. As a result, the wetland was flooded with abnormally high water (1 meter) for an abnormally long time (4 months). Plant roots were thus drowned with no oxygen source and consequently died. This hypothesis is strengthened by the survival of trees and plants along higher grounds at the wetland perimeter. Similar observations were made at Isabela, where the drainage of the wetland was further hindered by a paved bike path. Although some effort was made to allow for drainage under the paved path, it was not sufficient to completely drain the wetland following hurricane María. Therefore, although trees were likely impacted by wind damage, it was prolonged high flood waters that ultimately killed most of the forest. This flooding also killed any existing seeds and seedlings. Thus, unlike the other sites where viable propagules (germinated seeds) and seedlings were observed, there are very few to no recruits capable of regenerating the forest at Isabela and Punta Tuna. For these reasons, active management involving extensive planting will be necessary at these sites to hasten recovery to pre-hurricane similarity.

F. Recommendations

Recommendations for each site vary depending upon extent and cause of damage. Extensive mortality caused by chronic hydrology changes requires extensive repairs to geomorphology in order to restore sustainable conditions, as well as parallel restoration of woody vegetation through planting. Sites in which relatively minor wind damage was the primary problem require only constant monitoring to ensure natural recovery progresses satisfactorily. Specific recommendations are given in Table 5.

Table 5 specific site recommendations. Variations in recommendations depend on extent and cause of mortality, with hydrologically altered sites requiring more extensive repairs.

Site Name	Reclamation Recommendation
Jobos Isabella	1) Restore hydrology: a. Remove deposition under bike train bridges and improve outlet with a constructed channel b. Establish an MOU with USACE regulatory and other stakeholders to allow future maintenance of the channel outlet to be conducted as needed c. Install fill islands/peninsulas for depth diversity to increase resilience d. Replace fill portion of bike path with elevated trail 2) Monitor hydrology: a. Install monitoring wells equipped with recorders for water level and salinity 3) Rehabilitate mangrove vegetation a. Plant mangrove saplings 4) Monitor plant succession and mangrove recovery a. Assess vegetation structure through on the ground measurements of tree and seedling densities b. Assess landscape scale vegetation coverage through unmanned aerial vehicles at each site
Punta Tuna	1) Restore hydrology: a. Improve outlet from wetland system to ocean (maintenance will be needed) b. Establish an MOU with USACE regulatory and other stakeholders to allow future maintenance of the channel outlet to be conducted as needed 2) Monitor hydrology: a. Install monitoring wells equipped with recorders for water level and salinity 3) Rehabilitate mangrove vegetation a. Plant mangrove saplings 4) Monitor plant succession and mangrove recovery a. Assess vegetation structure through on the ground measurements of tree and seedling densities b. Assess landscape scale vegetation coverage through unmanned aerial vehicles at each site

Cucharillas/ Malaria Channel	1) Restore hydrology: a. Funding /Repair/ Management improvements are needed at pump station/ tide gates for reestablishing marine -terrestrial connectivity and prevention of flooding episodes. 2) Monitor hydrology: a. Install monitoring wells equipped with recorders for water level and salinity 3) Rehabilitate mangrove vegetation a. Plant mangrove saplings 4) Monitor plant succession and mangrove recovery a. Assess vegetation structure through on the ground measurements of tree and seedling densities b. Assess landscape scale vegetation coverage through unmanned aerial vehicles at each site
Torrecillas/ Pinones	1) Monitor hydrology: a. Install monitoring wells equipped with recorders for water level and salinity 2) Rehabilitate mangrove vegetation a. Plant mangrove saplings 3) Monitor plant succession and mangrove recovery a. Assess vegetation structure through on the ground measurements of tree and seedling densities b. Assess landscape scale vegetation coverage through unmanned aerial vehicles at each site
Punta Santiago	1) Monitor hydrology: a. Install monitoring wells equipped with recorders for water level and salinity 2) Rehabilitate mangrove vegetation a. Plant mangrove saplings 3) Monitor plant succession and mangrove recovery a. Assess vegetation structure through on the ground measurements of tree and seedling densities b. Assess landscape scale vegetation coverage through unmanned aerial vehicles at each site

For the rehabilitation of the wetland sites, based on restoration of mangrove forested vegetation and restoring and maintaining optimal hydrological conditions, the estimated costs based on personal communication with Ambienta Environmental Consulting Services, are \$30 / m^2 in remote locations, and \$15 / m^2 in urban locations. Isabela and Punta Tuna represent remote locations, while Cienaga las Cucharillas represents an urban location. Additionally, the modification of site geomorphology to restore hydrology through small earth moving projects will require a rough estimate of \$250,000 at Isabela and Punta Tuna. At Cienaga las Cucharillas, extensive repairs are required at the pump/gate station and this is estimated at \$1,000,000. These hydrological restoration projects will be carried out by the Department of Natural Resources and Environment of Puerto Rico (DRNA). Finally, the installation, maintenance, and operation of wells to monitor site hydrology and water chemistry will require $10,000 at each site over a 5-10 year period. Table six establishes the costs per specific site as each site has different rehabilitation/restoration requirements.

Table 6 Estimated costs for coastal wetland monitoring and rehabilitation at the five sites across Puerto Rico. Costs assume $30/m^2

Site	Passive Monitoring	Hydrology Rehabilitation	Vegetation Rehabilitation	Total
Isabela	$5000.00	$250,000	$4,500,000 /20 hectares	$4,755,000
Punta Tuna	$5000.00	$250,000	$4,500,000 /20 hectares	$4,755,000
Ciénaga las Cucharillas	$5000.00	$1,000,000	$2,250,000 /10 hectares	$2,505,000
Punta Santiago	$5000.00	$0	$0	$5000.00
Piñones	$5000.00	$0	$0	$5000.00
	$25,000	$750,000	$11,250,000	**$12,025,000**

G. References

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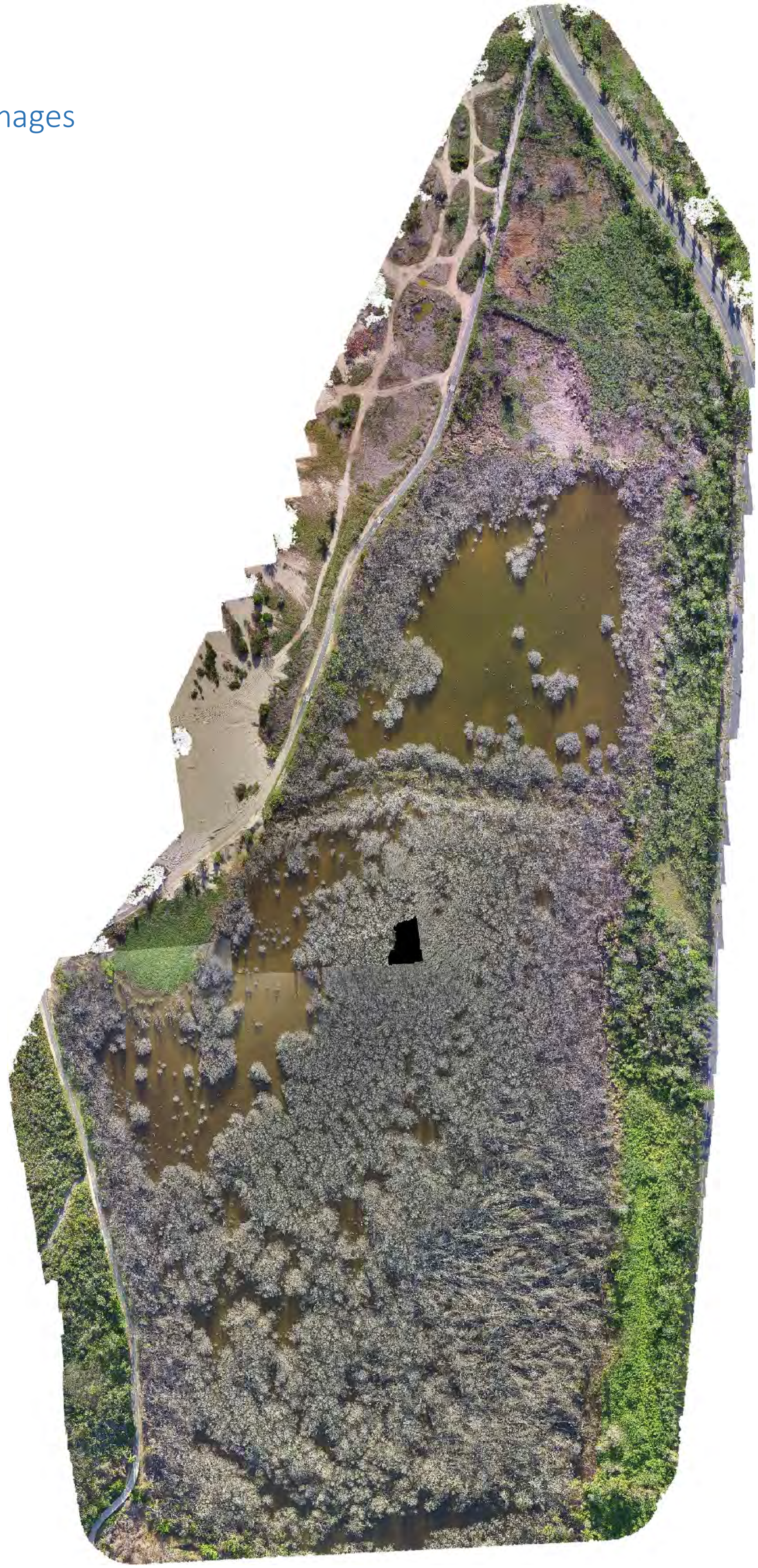
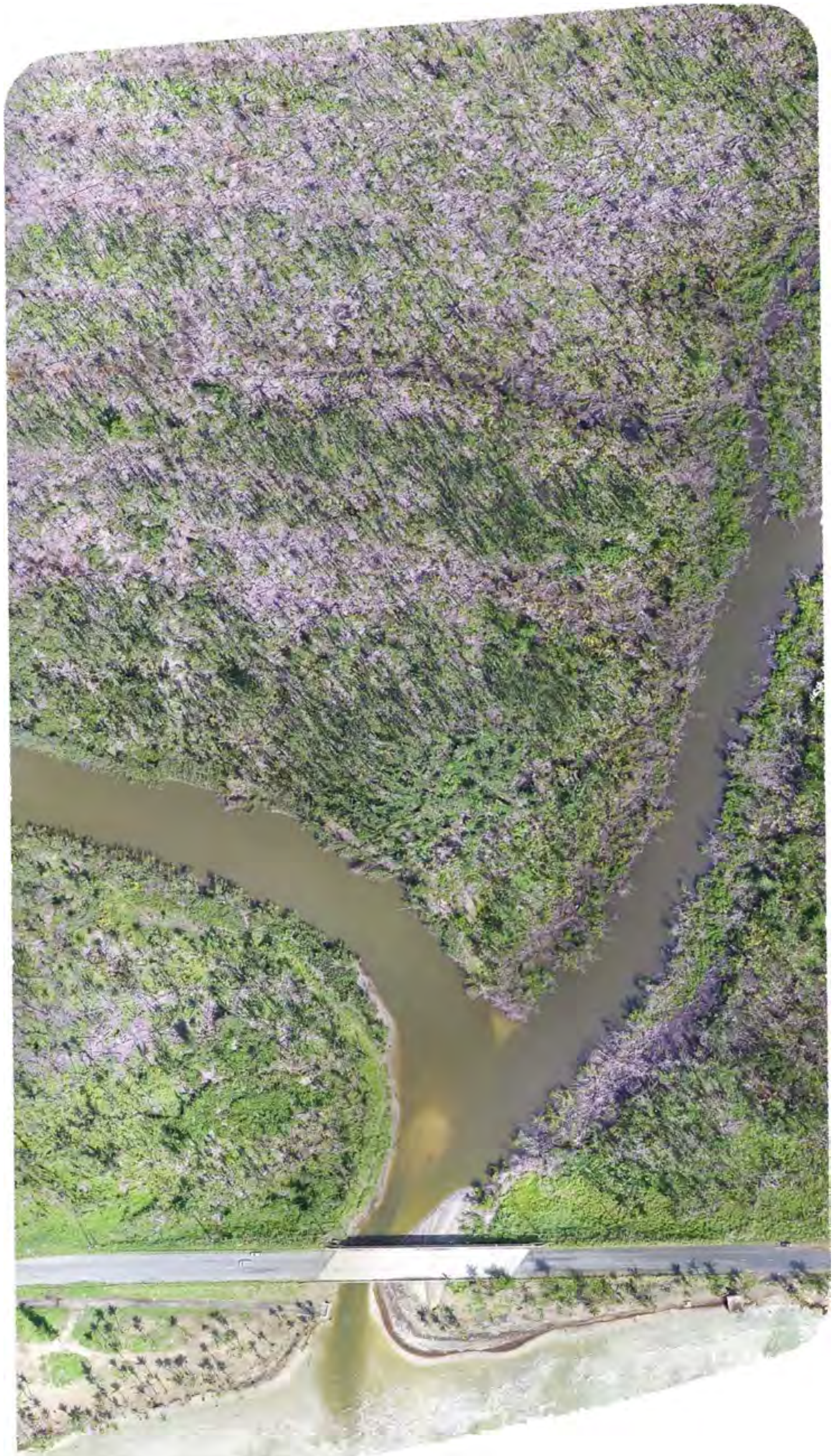
Appendix A – Aerial Images

Isabela, April 2018



Punta Santiago, April 2018



Punta Tuna, April 2018

Appendix A – Aerial Images

Ciénaga Cucharillas, April 2018

Appendix B – On Site Vegetation and Water Chemistry Measurements

Isabela

<table>
<tr><td>Location:</td><td colspan="15">Isabela, Puerto Rico</td></tr>
<tr><td>Date / Time:</td><td colspan="15">April 25, 2018. 9:30am – 12:00pm</td></tr>
<tr><td>Comments:</td><td colspan="15">Plots Coordinates:
1. 18.5138 –67.0518
2. 18.5139 -67.0510
3. 18.5139 -67.0500
The wetland was flooded roughly ten centimeters above the highest pneumatophores, suggesting the water level was higher than normal. All trees were dead except those on elevated ground, such as along the side of the highway and the bike path. Alive propagules were also only visible along these higher lands.</td></tr>
<tr><td></td><td>Salinity ppt</td><td>Temp °C</td><td>DO</td><td>pH</td><td>Water Depth (cm)</td><td># Dead Trees</td><td># Alive Trees</td><td colspan="3"># Alive Seedlings/ Propagules (m^{-2})</td><td colspan="3"># Pneumat Ophores (m^{-2})</td><td>% Trees as Mangroves</td><td>% Herbaceous</td><td>% Grass</td></tr>
<tr><td>Plot 1</td><td>28.66</td><td>27.1</td><td>1.41</td><td>5.25</td><td>10</td><td>9</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>100%</td><td>0%</td><td>0%</td></tr>
<tr><td>Plot 2</td><td>29.2</td><td>27.3</td><td>2.6</td><td>5.27</td><td>20</td><td>19</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>100%</td><td>0%</td><td>0%</td></tr>
<tr><td>Plot 3</td><td>29.5</td><td>28</td><td>3.44</td><td>6.29</td><td>20</td><td>14</td><td>0</td><td>0</td><td>0</td><td>0</td><td>4</td><td>14</td><td>10</td><td>100%</td><td>0%</td><td>0%</td></tr>
</table>

Punta Tuna

Location:	Punta Tuna, Puerto Rico
Date / Time:	April 21, 2018. 9:30am – 12:00pm
Comments:	Plots Coordinates: 1. 17.9975, –65.8793 2. 17.9956, -65.8804 3. 17.9961, -65.8815 The wetland was recently drained after being flooded for nearly four months following the hurricane. Water marks were visible on trees suggesting a flood level of roughly one meter. All trees were dead except those on higher grounds.

	Salinity ppt	Temp °C	DO	pH	Water Depth (cm)	# Dead Trees	# Alive Trees	# Alive Seedlings/ Propagules (m^{-2})			# Pneumat ophores (m^{-2})			% Trees as Mangroves	% Herbaceous	% Grass
Plot 1	28.66	27.1	1.41	5.25	10	9	0	0	0	0	0	0	0	100%	0%	0%
Plot 2	29.2	27.3	2.6	5.27	20	19	0	0	0	0	0	0	0	100%	0%	0%
Plot 3	29.5	28	3.44	6.29	20	14	0	0	0	0	4	14	10	100%	0%	0%

Ciénaga Cucharillas

<table>
<tr><td>Location:</td><td colspan="16">Ciénaga Las Cucharillas, Cataño PR</td></tr>
<tr><td>Date / Time:</td><td colspan="16">April 21, 2018. 9:00 – 12:15</td></tr>
<tr><td>Comments:</td><td colspan="16">Plots Coordinates:
1. 18.43714 -66.13325
2. 18.43653 -66.13456
3. 18.43686 -66.13489
The wetland was saturated with water, possibly to rainfall and water coming from the Malaria Channel. In plots 2 and 3, a depth of five centimeters to 4-5 cm of water were measured. Sedges (Cyperaceous), twines running thru the soil (sapindaceae), woody herbaceous no taller than 3 feet were considered herbaceous. For grasses only were considered species from the Poaceae family.</td></tr>
<tr><td></td><td>Salinity ppt</td><td>Temp ºC</td><td>DO</td><td>pH</td><td>Water Depth (cm)</td><td># Dead Trees</td><td># Alive Trees</td><td colspan="3"># Alive Seedlings/ Propagules</td><td colspan="3"># Pneumat ophores</td><td>% Trees as Mangroves</td><td>% Herbaceous</td><td>% Grass</td></tr>
<tr><td>Plot 1</td><td>17</td><td>25</td><td>NA</td><td>7.23</td><td>NA</td><td>16</td><td>2</td><td>0</td><td>0</td><td>0</td><td>24</td><td>48</td><td>n/a</td><td>100%</td><td>42%</td><td>6%</td></tr>
<tr><td>Plot 2</td><td>7.5</td><td>24</td><td>NA</td><td>7.34</td><td>4-5cm</td><td>3</td><td>1</td><td>1</td><td>0</td><td>0</td><td>8</td><td>0</td><td>2</td><td>93%</td><td>10.4%</td><td>0%</td></tr>
<tr><td>Plot 3</td><td>26</td><td>25</td><td>NA</td><td>5.2</td><td>4-5 cm</td><td>5</td><td>6</td><td>0</td><td>0</td><td>1</td><td>4</td><td>14</td><td>0</td><td>100%</td><td>1%</td><td>0%</td></tr>
</table>

Punta Santiago

Location:	Punta Santiago, Puerto Rico															
Date / Time:	April 21, 2018. 2:30am – 4:30pm															
Comments:	Plots Coordinates: 1. 18.1757, –65.7397 2. 17.9956, -65.8804 3. 17.9961, -65.8815 The wetland was recently drained after being flooded for nearly four months following the hurricane. Water marks were visible on trees suggesting a flood level of roughly one meter. All trees were dead except those on higher grounds.															
	Salinity ppt	Temp °C	DO	pH	Water Depth (cm)	# Dead Trees	# Alive Trees	# Alive Seedlings/ Propagules (m^{-2})			# Pneumatophores (m^{-2})			% Trees as Mangroves	% Herbaceous	% Grass
Plot 1	28.66	27.1	1.41	5.25	10	9	0	0	0	0	0	0	0	100%	0%	0%
Plot 2	29.2	27.3	2.6	5.27	20	19	0	0	0	0	0	0	0	100%	0%	0%
Plot 3	29.5	28	3.44	6.29	20	14	0	0	0	0	4	14	10	100%	0%	0%

Bosque Estatal Piñones

Location:	Bosque Estatal de Piñones ,Carolina, PR															
Date / Time:	April 26, 2018. 9:00 – 12:15															
Comments:	Plots Coordinates: 1. 18.4427, -65.9568 2. 18.4436, -65.9572 3. 18.4434, -65.9565															
	Salinity ppt	Temp °C	DO	pH	Water Depth (cm)	# Dead Trees	# Alive Trees	# Alive Seedlings/ Propagules			# Pneumat ophores			% Trees as Mangroves	% Herbaceous	% Grass
Plot 1	21.9	27.8	1.4	7.7	10 cm below ground	11	29	5	3	1	0	0	0	100%	0%	0%
Plot 2	28.2	27.5	2	7.7	4-5cm below ground	15	35	2	0	0	8	5	2	100%	0%	0%
Plot 3	22.3	27.6	0.4	7.7	2 cm below ground	2	9	10	3	4	0	0	0	100%	0%	0%

Appendix C – Antilles Rapid Assessment Methodology (ARAM) Site Selection

Post-Hurricane Maria Puerto Rico's Coastal Wetlands Sites Details

Sites:	Wetland Class:	Municipality	Region	Latitude	Longitude
Boqueron 6 new	EEM	Cabo Rojo	West	18°1'06.43"N	67°9'45.64"W
Tortuguero 4 new	EEM	Manati	North	18°27'15.60"N	66°26'37.24"W
Ponce 2	EEM	Ponce	South	17°58'47.56"N	66°39'28.42"W
Espiritu Santo	EEM	Rio Grande	North	18°24'11.21"N	65°49'12.88"W
EEM Roosevelt Raods	EEM	Ceiba	East	18°12'39.51"N	65°38'20.97"W
Bosque Piñones site Ref	EFO	Loiza	North	18°26'23.22"N	65°57'37.09"W
Bahia JOBANNER	EFO	Salinas	South	17°55'59.69"N	66°15'11.16"W
Boqueron 1	EFO	Cabo Rojo	West	18°1'01.07"N	67°9'32.12"W
Laguna Prieta	EFO	Fajardo	East	18°22'31.85"N	65°38'37.01"W
Punta Tuna	EFO	Maunabo	East	17°59'42.74"N	65°52'54.06"W
Corredor Eco. (CENE) A	PEM	Luquillo	East	18°21'49.84"N	65°42'12.53"W
La Esperanza	PEM	Manati	North	18°28'24.46"N	66°30'48.52"W
Maunabo 2	PEM	Maunabo	East	17°59'58.08"N	65°52'42.55"W
Arroyo 1	PEM	Arroyo	South	17°57'49.68"N	66°2'35.82"W
CT 3	PEM	Arecibo	North	18°28'24.61"N	66°41'50.38"W
Pterocarpus Dorado	PFO	Dorado	North	18°28'6.04"N	66°16'56.99"W
Punta Viento	PFO	Patillas	South	17°58'23.95"N	65°58'43.43"W
Palmas del Mar	PFO	Humacao	East	18° 5'34.36"N	65°48'2.16"W
El Manantial	PFO	Vega Baja	North	18°28'6.57"N	66°25'23.35"W
Finca Virginia 1	PFO	Loiza	North	18°24'58.82"N	66°54'45.80"W

Table 2: Pre- and Post-Hurricane Site ARAM Index Scores Classified by Condition Category.

Site	Pre-Hurricane (November 2016)	Pre-Hurricane Condition Category*	Post-Hurricane (April 2018)	Post-Hurricane Condition Category*
EFO Boquerón 1	152	Good	98	Poor
EFO Bosque Piñones Reference	202	Good	160	Fair
EFO JOBANNER	183	Good	171	Good
EFO Laguna Prieta	183	Good	117	Fair
EFO Punta Tuna	167	Good	92	Poor
EEM Boquerón 6 New	110	Fair	110	Fair
EEM RN Espíritu Santo Ref	150	Good	119	Fair
EEM Original Site_RR Ref	169	Good	144	Good
EEM Ponce 2	160	Good	150	Good
EEM Tortuguero 4 New	175	Good	163	Good
PFO El Manantial	169	Good	146	Good
PFO Finca Virginia 1	208	Good	152	Fair
PFO Palmas del Mar	185	Good	88	Poor
PFO Pterocarpus Dorado	185	Good	129	Fair
PFO Punta Viento Ref	204	Good	135	Good
PEM Arroyo 1	129	Good	129	Good
PEM Corredor Ecológico A	150	Good	146	Good
PEM CT3	146	Good	135	Good
PEM La Esperanza	152	Good	156	Good
PEM Maunabo 2	115	Fair	104	Fair

Appendix D- NRCS Hydrology and Geomorphology Assessment (Draft)

USDA

United States Department of Agriculture

Natural Resources Conservation Service

National Design, Construction, and Soil Mechanics Center

501 W. Felix, Bldg. 23

Fort Worth, Texas 76115

Phone: 817.509.3752

Fax: 817.509.3753

Subject: ENG - Trip Report – Mangrove Wetlands
Bastrop County, Texas
April 2-9, 2018

Date: April 11, 2018

To: Juan C Hernandez

NCR Erosion and Sedimentation Team Lead

Natural Resources Conservation Service

Hato Rey, Puerto Rico

File Code: 210-7

PURPOSE: The goal of the subject trip was to investigate several mangrove wetland sites that were impacted because of Hurricane Maria. Five locations were visited and examined during the subject trip. These include the sites designated Torrecillas/Piñones, Cucharillas/Malaria Channel, Jobos Isabela, Punta Tuna and Punta Santiago. The team conducted a reconnaissance level analysis to assess if these tidally influenced coastal wetlands were adversely impacted by the 2017 storm and if they would benefit from a restoration effort.

PARTICIPANTS:

Several interested parties and local stakeholders were consulted during the subject trip. The primary participants are listed below:

- Benjamin Branoff[1], PhD candidate, Department of Biology, University of Puerto Rico – Rio Piedras
- Elvira Cuevas[2], Professor of Ecology and PI for study, University of Puerto Rico – Rio Piedras
- Jorge Ortiz[3], Professor of Limnology. University of Puerto Rico – Rio Piedras
- Elix Hernandez-Figueroa[4], MS student, University of Puerto Rico – Rio Piedras
- Jesus Rodriguez[5], Hydrogeologist, USGS, retired, San Juan, Puerto Rico
- Juan C Hernandez[6], NCR Erosion and Sedimentation Team Lead, Hato Rey, Puerto Rico
- Barry Southerland[7], Geomorphologist, NRCS-WNTSC, Fort Worth
- Jon Fripp[7], Stream Mechanics Civil Engineer, NRCS-NDCSMC, Fort Worth

1- Attended meetings in university and sites Torrecillas/Pinones, Cucharillas/Malaria Channel, Jobos Isabella, Puta Tuna.
2- Attended meetings in university and site Cucharillas/Malaria Channel
3- Attended meetings in university at site Puta Tuna.
4- Attended meetings in university and site Cucharillas/Malaria Channel
5- Attended meetings at sites Cucharillas/Malaria Channel and Puta Tuna
6- Attended meetings at the motel
7- Attended meetings in university, motel and sites Torrecillas/Pinones, Cucharillas/Malaria Channel, Jobos Isabella, Puta Tuna and Punta Santiago.

BACKGROUND:

Hurricane Maria was the deadliest storm in a very active 2017 hurricane season. Hurricane Maria struck Puerto Rico on as a category 4 on morning of September 20, 2017. The storm traveled across the island impacting infrastructure and the environment. It was the 10th most intense tropical storm on record for the Atlantic and impacted Puerto Rico two weeks after Hurricane Irma caused extensive damage. A map illustrating the path of hurricanes and the sites reviewed as part of the subject trip are provided in Figure 1.

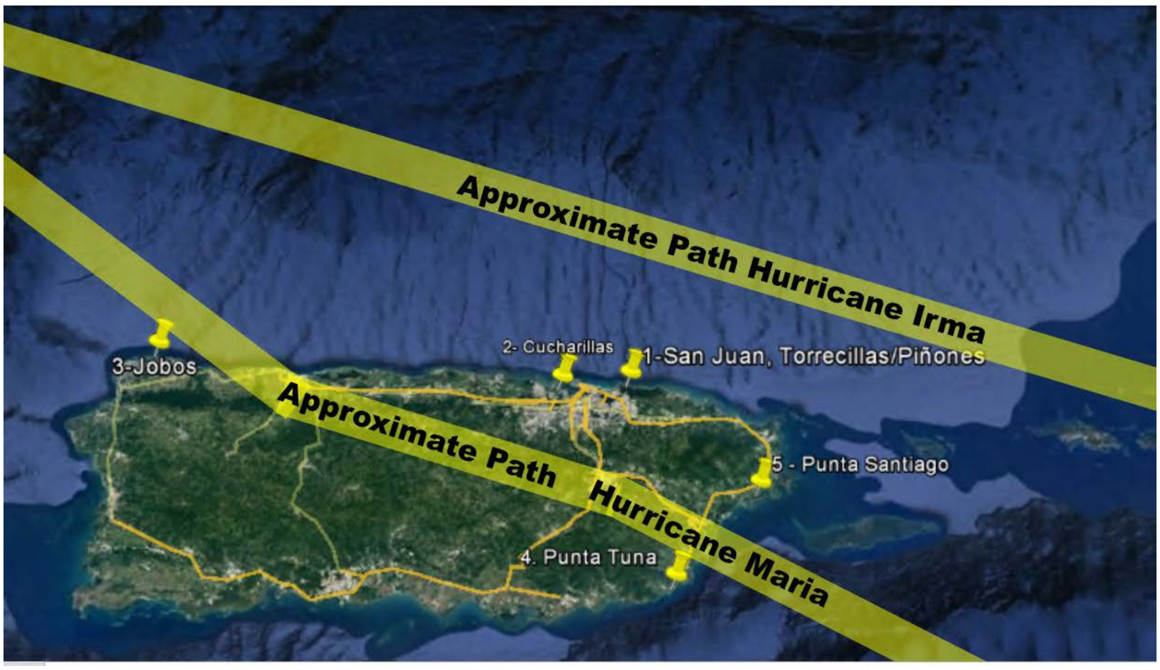


Figure 1: Sites reviewed as part of study and approximate storm paths of hurricane eye

MANGROVE ECOLOGY AND HYDROLOGY: Mangroves belong to a distinct plant family called halophytes. These coastal plants have evolved to survive in harsh saline and semi-saline environments along tropic and sub-tropic coastlines and intertidal estuaries. It is the mangroves ability to survive and process salt water through its unique lenticel physiology that enables them to establish within this harsh environment.

Mangrove physiology and its elevations relevant to ocean tidal stage and freshwater runoff provides the fundamental basis for survival. Red Mangrove, Black Mangroves, and White Mangroves are found throughout the world on coastlines between 28 degrees North and 28 degrees south of the equator. In Puerto Rico the red (Rhizophora mangle), white (Laguncularia racemosa) and black (Avicennia germinans) mangroves occupy different ecological niches and have slightly different chemical compositions so the carbon content varies between the species as well between the different tissues of the plant e.g. leaf matter vs roots. In Puerto Rico there is a clear succession of these three trees from the lower elevations which are dominated by red mangroves to farther inland with a higher concentration of white mangroves. Mangrove forests are an important part of the cycling and storage of carbon in tropical coastal ecosystems. Figures 2 and 3 show red and white mangroves in Puerto Rico.

Figure 2: White mangrove pneumatophores next to Suarez River, Puerto Rico.

Figure 3: Red Mangrove community at Piñones Reserve, Puerto Rico.

A VITAL RESOURCE FOR PUERTO RICO: Mangrove forests provide many of the resources upon which coastal people depend upon for the survival and livelihood for food and protection. At low tide, people can walk across tidal flats to collect clams, shellfish, and shrimp. At high tide, fish move in to feed among the protection of mangrove roots, turning the marshy land into rich fishing grounds. The mangrove trees themselves provide fuel, medicines, tannins, and wood for building houses and boats. Mangroves provide critical protection for humans and fauna for hurricane, tidal waves and tsunamis.

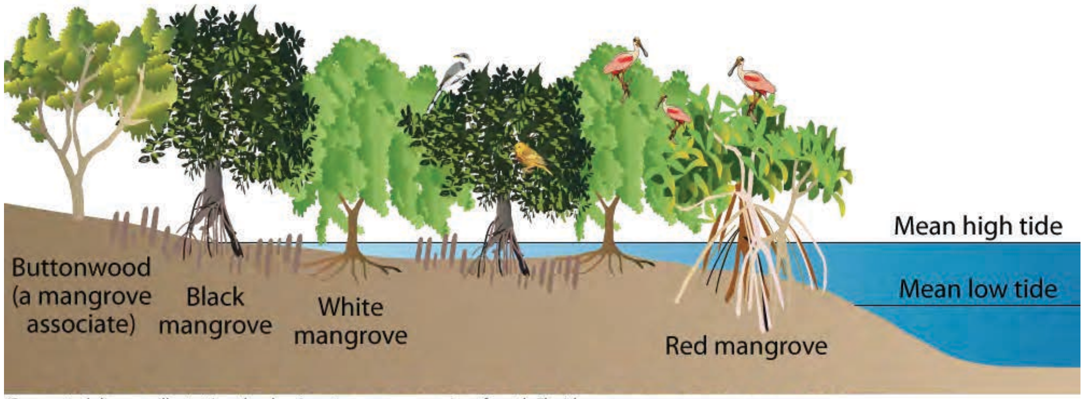
Puerto Rico has lost much of its original mangrove wetland forests. It is estimated that approximately 75% of the original mangrove wetland forests have been significantly altered or destroyed since European discovery. Coastal Mangrove wetland forests provide numerous economic and environmental benefits including:

1- Protection from storm surge erosion and flooding: Mangrove wetland forests provide physical barriers to storms. The root systems of the mangrove trees provide erosion protection as well as dissipate wave energy. In addition, the wetland forest area provides for water storage from rain fall occurring coincident with a hurricane.
2- Water quality: The plant provides physical and biological water filtration and treatment
3- Recreation: Eco tourism in attractive mangrove systems is a major economic source
4- Environmental: The unique root systems of a mangrove forest provide a quiet resting and nursery area for many marine organisms. It is estimated that upwards of 80% of Caribbean aquatic organisms are depended on mangrove wetland forests. In addition, many bird species utilize mangrove wetland forests.

Mangroves provide ideal breeding grounds for much of the world's fish, shrimp, crabs, and other shellfish. Many fish species, such as barracuda, tarpon, and shook, find shelter among the mangrove roots as juveniles, head out to forage in the seagrass beds as they grow, and move into the open ocean as adults. An estimated 75 percent of commercially caught fish spend some time in the mangroves or depend on food webs that can be traced back to these coastal forests.

> *"Mangroves are like the kindergarten, seagrasses are the secondary schools, and coral reefs are the high schools and colleges for fishes! And, once [the fishes] graduate from university, they return to kindergarten to spawn!"*
> *--Khun Pisit, cofounder of Thailand's Yad Fon mangrove preservation project*

Of the three principle mangroves: red, black, and white, it was observed that the black mangrove genus Avicennia germinans had the highest mortality rate due to both long periods of submerged pneumatophores and high hurricane wind damage on larger trees. White mangroves had volunteer shoot regrowth on the fringe of the perched water table sites such as Punta Tuna and Jobos de Isabella. A conceptual drawing for mangrove species in Florida located relative to man high and low tide is provided in Figure 4. This figure illustrates a generalized location of mangroves relative to the mean high and low tide.



Conceptual diagram illustrating the dominant mangrove species of south Florida.
Diagram courtesy of the Integration and Application Network (ian.umces.edu), University of Maryland Center for Environmental Science. Source: Kruczynski, W.L., and P.J. Fletcher (eds.). 2012. Tropical Connections: South Florida's marine environment. IAN Press, University of Maryland Center for Environmental Science, Cambridge, Maryland. 492 pp.

Figure 4: Generalized location of Red, White and Black mangrove hydrologic elevations relative to mean high tide and mean low tide. Diagram from "Tropical Connections: South Florida's marine environment"

MANGROVES AND HURRICANES: Hurricanes have impacted the Caribbean in the past and will do so in the future. Mangrove wetland forests are adapted to withstand large storms and recover. However, extreme events can significantly impact mangroves to a point where natural recovery can be difficult if not nearly impossible. There are three main mechanisms than mangrove wetland forests are impacted including:

1- Wind damage: Significant and prolonged winds can strip leaves from the branches reducing the available energy for the tree. Winds can also topple trees.
2- Storm Surge and Flooding: While mangroves are biologically adjusted to thrive in wet environments, prolonged high water can drown them by inundating the root systems (especially the pneumatophores.) Ponded sea water will evaporate and increase salinity over the threshold the mangroves can tolerate. The excessive flooding can happen during the storm, but a prolonged inundation is usually the result of morphological changes induced by silting or filling the existing channels from the wetland. Sometimes coastal dunes are pushed up during hurricane events blocking mangrove wetland inlet-outlet. This is often exacerbated by coastal infrastructure such as elevated roads.
3- Sedimentation: Storm surges can result in sediment deposition on the wetland forest floor. Excessive sedimentation can interfere with gas exchange between roots and soil of the mangrove trees and result in tree death.

FINDINGS:

The team visited each of the five sites. The sites are large and walking through them is difficult. Time restraints did not allow for a thorough examination, but the team was able to conduct a targeted, reconnaissance level investigation.

The hydrologic flow paths and geomorphology were examined to assess terrestrial/marine connectivity. This was facilitated with aerial mapping survey measurements on the site. Soils and vegetation were examined to quantify both past and current conditions. Grab samples for water quality assessments were conducted as indicators of current function as well as impacts of possible damage in watershed infrastructure. The upper watershed was also reviewed. Photographs of some of the assessments are shown in Figures 5, 6, 7 and 8.

Figure 5: Soil assessments and surveys were conducted to assess past and current conditions

Figure 6: The team conducted field level water quality assessments for TDS, salinity, pH, Nitrates, Nitrites, Total Chlorine, Coliform bacteria and E.coli

Figure 7: Vegetation condition and recovery were assessed. The current state of vegetation as well as estimate of flooding were discussed at each site.

Figure 8: Areas in the upper watershed were reviewed. Much of the area is steep and developed, yet vegetation appears to be recovering

Site status, function and transitions were discussed on the sites, in the car between the sites, at the hotel and the university, and over dinner. Several options were considered and are briefly summarized below:

PLANNING: Considerable preplanning and literature search, GIS, and verbal discussion was completed prior to field visits. The non NRCS members of the team have considerable background and expertise in the mangrove systems of Puerto Rico. The team discussed the importance and use of a systematic planning approach for any work. The use of the watershed as a fundamental unit for both assessment and planning was also agreed upon. The nine steps of planning as employed by NRCS for conservation activities were discussed in detail by the team. The non NRCS members of the team were not as familiar as the NRCS members with the planning process used by the NRCS. Therefore, upon request, this process is summarized in this report for non NRCS employees with a focus on the current mangrove project.

The 9-step planning process used by the USDA-NRCS to plan soil and water conservation techniques and practices. The diagram shown in Figure 9 illustrates the USDA-NRCS 9 step area-wide planning process. Priority resource concerns can be adjusted to match the watershed goals/objectives and are emphasized in each planning step. USDA-NRCS conservation planning standards, inputs, and products for each of the planning steps can be referenced; however, the primary focus is on providing information necessary for applying this process to assessing the problems and opportunities for the mangrove wetland forests in Puerto Rico.

> Steps 1 and 2: Fripp and Southerland attended a meeting on April 3rd at the University of Puerto Rico with Dr. Elvira Cuevas, Professor of Ecology, Benjamin Branoff, PhD candidate, Department of Biology (Field Contact), and Dr. Felix Ortiz, Professor of limnology to discuss and refine problems and objectives. Dr. Cuevas and Mr. Branoff provided an excellent overview of the five impacted sites and explained the prioritization of these sites. Of the five sites Dr. Cuevas pointed out Punta Tuna appeared to have the highest mangrove mortality. The resource problems are the accelerated loss of valuable mangrove forests likely due to hydrologic conditions and wind damage. The objectives were to investigate each site and define the cause and effect of mangrove damage.

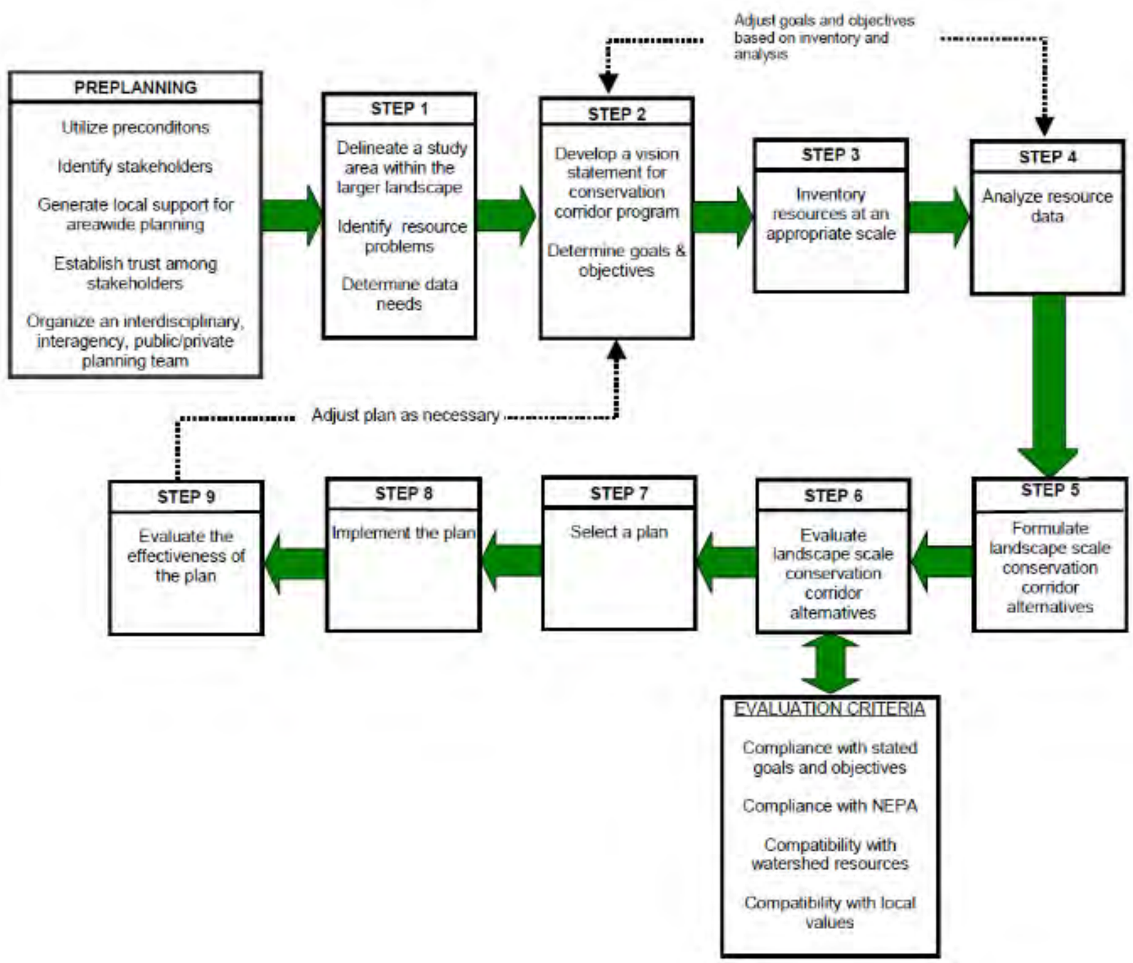


Figure 9: The NRCS 9 step planning process

<u>Steps 3 and 4:</u> Southerland and Fripp visited all five sites and completed inventory and analysis. They prepared and spent considerable time with the participants in the field for inventory with the listed participants on-site, with the exception of Juan Hernandez.

<u>Steps 5 and 6:</u> These steps were addressed by Fripp and Southerland both on-site and in team planning at the end of each day.

<u>Steps 7, 8 and 9</u>: are to be completed by shareholders.

<u>THE HYDROGEOMORPHIC (HGM) CLASSIFICATION SYSTEM:</u> A functional assessment useful in planning, design and monitoring can be enhanced with using the tools in the HGM classification approach. The HGM Approach is a multi-agency effort involving the U.S. Army Corps of Engineers, the Environmental Protection Agency, Federal Highway Administration, U.S. Fish and Wildlife Service and the NRCS. The HGM system was developed by Brinson in “A Hydrogeomorphic Classification for Wetlands”, 1993, and the use of the HGM system in the development of functional assessment models was developed by Smith, et al. in “An Approach for Assessing Wetland Functions Using Hydrogeomorphic Classification, Reference Wetlands, and Functional Indices”, 1995. The classification system is a hierarchical

framework, beginning with seven broad HGM classes: RIVERINE, SLOPE, LACUSTRINE FRINGE, ESTUARINE FRINGE, MINERAL FLATS, ORGANIC FLATS, AND DEPRESSIONAL. The use of upper case letters here is in keeping with the HGM taxonomic system. The HGM classes are differentiated by three parameters:

1. Landscape Position - the watershed position of the watershed
2. Dominant Water Source – precipitation, streamflow, surface runoff, groundwater, tides or lake effects
3. Hydrodynamics – magnitude and direction of inflow and outflow vectors

The use of landscape position separates wetlands based on their locations on floodplains, lake shorelines, estuaries, interfluves, headwaters, and closed topographic depressions. The dominant water source parameter separates wetlands based on different water sources, such as surface runoff, direct precipitation, groundwater, tidal inflows, and lake fluctuations. And hydrodynamics separates wetlands based on the directions of inflow and outflow of water in the liquid phase. These directions are expressed as horizontal or vertical, and uni-directional or bi-directional. This HGM classification is useful in aggregating wetlands with similar functions. It is not intended to be a “valuation” procedure that ranks one wetland as better, or worse, than another.

HGM guidebooks have been developed for a variety of areas across the country. It is suggested that stakeholders obtain and consult "Regional Supplement to the Corps of Engineers Wetland Delineation Manual: Caribbean Islands Region” (Technical Report ERDC /EL TR-11-4) and “A Hydrogeomorphic Classification for Wetlands” (Technical Report WRP-DE-4). These documents may be useful in providing some guidance in the assessment, review, study, restoration and management of this and other similar sites. Mangrove wetlands are typically in the riverine, fringe and depositional categories. Modifications of the HGM approach have been proposed. A mangrove specific classification system has been proposed by Lugo and Snedaker where mangroves are divided into five groupings based on hydrologic properties. A sketch is provided below in Figure 10. The team suggests that this classification system may facilitate communication and discussion among stakeholders including the US Army Corps of Engineers. Further subdivisions within this classification are often made to improve communication and analysis.

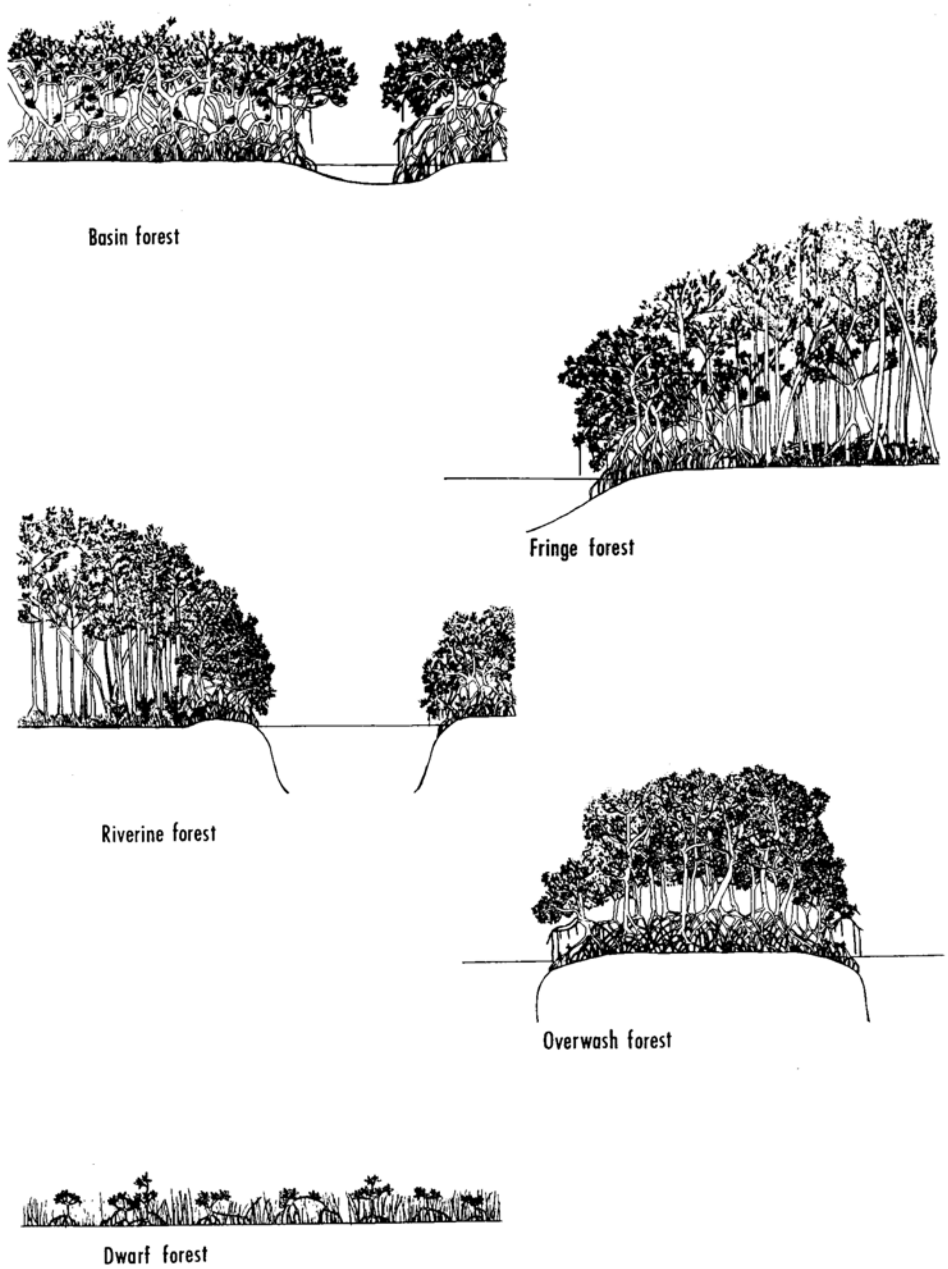


Figure 10: Five types proposed for mangroves in Florida by Lugo and Snedaker (1974) as

Illustrated in Wharton et al. (1977)

Torrecillas/Pinones: This site was visited on 4 April. The lower or park site is of primary concern. It is located at approximately N 18-26.546 W 65-57.415 and is referred to as the Laguna De Pinones area. Basin, Lagoon, and Riverine wetland types are present in this area. It is widely known and used for tourism. There are walking and kayaking trails and visitor areas present. Signage indicates that management is provided at least in part by the DRNA (Departamento De Recursos Naturales Y Ambientales / Department of Natural Resources and the Environment).

Much of the leaves have been removed during the storm by the high winds and several of the larger trees have been up-rooted. The upper canopy is nearly gone in areas. However, the team noted that the lower canopy appears to be recovering and healthy growth was observed. The team also visited Suarez Canal at approximate location N18-25.685 W65-59.362 which flows into the site. Photographs of the site are provided in Figure 11. A map image is provided in Figure 12.

Figure 11: Photographs on Laguna De Pinones area

Mr. Branoff reported that the area in the Laguna De Pinones had been inundated for approximately 2 weeks after Hurricane Maria but the efficient city drainage system had allowed waters to evacuate before flooding damage had been significant. Water gages installed and monitored as part of Mr. Branoff's research indicate that the hydro-period had largely returned to the pre-storm conditions.

The team noted that some interior drainage structures such as culverts likely reduce some of the natural flows in the lower portion of the system, but the roads are low and likely frequently overtopped. The tree species appear to have adapted to the current system. Mr. Branoff also noted that the high winds had stripped leaves from the black mangroves which had resulted in some mortality. Mr. Branoff noted that there is concern by some stakeholders that the bridge opening at the Baldorioty Expressway (on the Suarez Canal) may restrict some of the tidal exchange but the team did not observe or measure evidence of this at the time of the site visit.

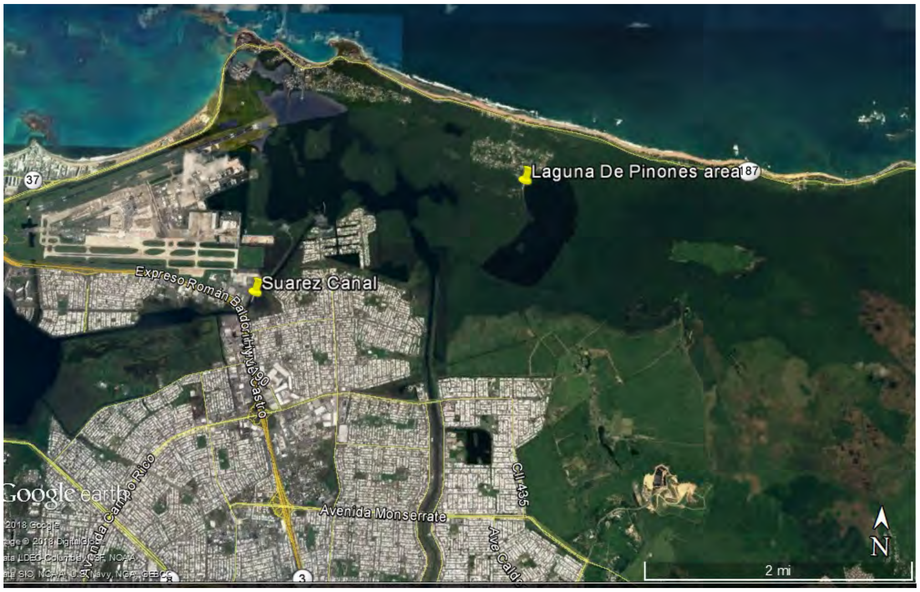


Figure 12: Google Earth image of Torrecillas/Pinones site. Pins indicate visited locations. Date of image is 7/2017, before the storm.

The team observed that the storm had appeared to impact restroom facilities. The high-water table in the park (lower area) may limit the effectiveness of treatments provided by septic systems. Water quality measurements were made at the two sites. Both sites areas that were visited by the team had brackish water at time of the visit and no nitrates/nitrites were measured. Trace amounts of free chlorine were measured at the site visited along the Suarez Canal which may indicate a break in a water line or a sewage treatment impact. However, the low amount is not a concern for the health of the wetland. Both sites exhibited coliform contamination with the E. coli measurements at in excess of 60 colonies per ml for one sample and TNTC (Too Numerous to Count) for a second sample at the Laguna De Pinones area. The pathogen contamination measured at the lagoon area was the largest of any of the grab samples analyzed during this trip. While these grab samples are not definitive, these high values may be due to damage suffered to the sewage treatment for the restroom facilities at the park. This may indicate a need for further water quality analysis and possible warnings needed for recreational use of the water.

The team believes that this site exhibits natural and healthy recovery from the storm. While the area looks different than it did pre-storm and is perhaps unattractive, it is recognized that big storms tend to up root and impact the big trees. Younger trees fill in the openings as they are exposed to more sunlight. Black, Red and White mangroves are present and alive. The current recon study indicates that **no significant restoration or reclamation efforts are necessary**.

The team suggests that **signage should be updated** to describe the storm and the recovery that is being observed. Some **dead limbs that are overhanging trails and roads should be trimmed** for safety concerns. Finally, it is suggested that the **mangrove area be monitored and studied** as it naturally responds to the storm damage. Big storms have occurred in the past and will occur again in the future. Lessons learned from how the specific trees as well as the system as a whole both responds and recovers from hurricanes will be useful for the analysis of future events.

<u>Cucharillas/ Malaria Channel:</u> This site was visited on 6 April. It is located at approximately N 18-26.135 W 66-08.038. The site is primarily a Riverine wetland type that drains through an excavated channel referred to as the Malaria Channel. The site is surrounded by development. The south-east portion has low income development and is subject to flooding. This site has been under long term academic study led by Dr. Elvira Cuevas who led the team on this visit.

Dr. Cuevas stated that the pump station at the mouth of the malaria channel had failed during the storm and that the entire area had been flooded for nine days after the storm. High winds had stripped the leaves from the larger trees during the storms. These trees had remained bare for three months. Leaves are seen during the current visit and Dr. Cuevas noted that the white mangroves appear to be recovering.

However, the water is not sufficiently saline to limit fresh water vegetation. Water samples taken from monitoring wells from below the surface is in the range of 25 to 30 ppt (nearly the seawater) but surface water is nearly fresh (measured at 350 ppm during visit). The team believes that this may indicate that there may be some subsurface exchange.

In areas, grasses may be out competing the young mangroves. If this condition is not changed, as the older mangroves die off, there is a concern that they will be replaced by freshwater species such as the grasses. Biologic water quality samples of the upstream area showed high levels (TNTC – Too Numerous to Count) of E Coli in the channel sediments and moderate levels (30 to 40 colonies per ml) in the flows. While these grab samples are not definitive, these high values may indicate that signage warning the public to avoid contact with the sediment is warranted. The coliform pathogen contamination was positive in all samples. Nitrogen was measured at trace. No chlorine was measured at time of the visit. Photographs of the site are shown in Figure 13.

Figure 13: Cucharillas area. Note trees are recovering but grasses are moving in. Photograph at right shows monitoring well

The team visited the main portion of the study area as well as the pump station at the mouth. This station includes tide gates and is located at approximate location N 18-26.844 W 66-08.161. This station controls exiting flows from the Cucharillas site. A map image is provided in Figure 14.

Figure 14: Google Earth image of Cucharillas/ Malaria Channel site. Pins indicate visited locations. Date of image is 1/2016. Later images had cloud cover

There was one pump station operator on duty at time of the site visit. No maintenance or operational logs were present at the site but the operator was very helpful and freely shared what he knew about the history and operation of the installation. The team was informed that the pump station was reportedly constructed in the late 1940s by the US Army Corps of Engineers but has been turned over to operation by Department of Public Works (DRNA). The pumps are used to remove water upstream of the station when the tide gates are shut. Their effective operation reduces the potential for upstream flooding. Installation of the pumps is for three 200 hp pumps but, at time of the visit, the team observed that one pump was missing, one was in-operative and one was working but in poor condition. The operator on site informed the team that single working pump could only be run for 20 to 30 minutes, three times a day. This operational pump was briefly turned on during the site visit but sounded like the pump operation sounded like there was a need for immediate maintenance. Therefore, the pump was shut down after a few minutes. The team observed portable pumps upstream of the site. The operator beloved that they were used during the storm. The team noted that they appeared to be inadequately maintained. The apparent limited operational capacity of the pump station may result in upstream flooding and a risk to life and property.

The tide gates were closed during the site visit. The team noted that tide gates are typically open during flow conditions such as present during the site visit to allow for natural tidal exchange. They are closed during storms. The operator stated that the tide gates have not been operated in the last six years because of debris that is present on the sill. The team did not observe excessive debris in the vicinity, but a complete examination was not possible due to water levels. There are slots for stop logs but there are no stop logs on site. The operator is not familiar with any maintenance being accomplished on the gates. The gates themselves show some corrosion indicating that they may have not been operated in some time. The gates are electrically powered but the operator said there is no power available. The team noted that the gates have the capacity to be manually operated. Photographs of the site are provided in Figure 15.

Figure 15: Pump station and tide gates. Note the three pump locations in the photo at right

The team believes that the ecologic function of the Cucharillas mangrove area is limited by the operation of the tide gates and pump station. The current operation of this station is adverse to the recovery and sustainability of the mangrove wetlands. The gates need to be operated so that they mimic as much as possible a natural tidal cycle. In addition, inadequate pump capacity places the upstream area at risk for flooding in populated areas. Finally, the in operation of the tide gates reduces natural flushing and is likely a contributor to adverse water quality and may increase the potential for disease outbreaks.

The pump station appears to be well designed but does not appear to be provided with sufficient man power and financial resources to be effectively operated. The success of any restoration work in the mangrove area is limited without improvements to the pump station. If the pump station is improved, the site may naturally recover. In addition, the current limited operational capacity of the pump station and tide gates may be a risk to life and property. Therefore, the team recommends **that no work be undertaken until the pump station and tide gates are repaired and the station is adequately staffed with personnel who are trained and empowered to maintain and operate the system**. Selective mangrove seedling plantings can be attempted but only on a study basis.

<u>Jobos Isabella Site:</u> This site was visited on 8 April. It is located at approximately N 18-30.805 W 67-03.399. The site is an Estuarine Fringe and a Basin wetland type. The site is bounded between a road and a paved bike path. It is in a tourist area and is well used. Ecologically oriented educational signage is present. The wetland area has standing water and the trees are bare of vegetation. An examination of historical aerial imagery indicate that the area has had open water in the past but it appears that this area may have expanded as result of the storm. The mangrove trees in the wetland area appear dead and are aesthetically unappealing. It is suspected that this may have a negative economic impact.

However, the team observed that red mangrove seedlings and some white mangroves along the high ground around the perimeter of the site are leafing out. The team believes that this growth will naturally revegetate and recover the interior if the hydrologic connectivity is improved. **Monitoring and documentation of this natural succession is suggested.** The Photographs of the wetland area are provided in Figure 16.

Figure 16: Photographs of the mangrove wetland in the Jobos Isabella site. Some leafing is observed on high ground along the edges

The pathway is elevated on cohesive fill material. Aerial imagery show that this path appears to have been in place since the early 1990s. This reduced the important natural connectivity of the mangrove wetland to the ocean. However, five foot-bridges through the path were installed which provide hydrologic connectivity with the ocean. This hydraulic connection is good but the limited nature of it reduces the resilience of the site to storms. The channel width through the bridges is limited to 7 feet. While it does not appear that all the bridges were constructed over consistently free flowing channels, none are currently draining the ponded area under current conditions. The team suspects that the storm filled the channels and part of the area under these bridges. This probably eliminated the ability of the mangrove area to drain. Storm overflow had filled the basin and through evaporation, increased the salinity. Photographs of some of the bridges are provided in Figure 17.

Figure 17: Photographs of the bike trail and foot bridges that limit the hydrologic connectivity

The team conducted a quick field survey of the site and found that the area is ponded in the mangrove wetland area. Water may be ponded 1.5 to 2 feet over what it was pre-storm. Temporary gages installed by the team during the visit indicate that the water in continuing to drain, albeit slowly. Mr. Branoff collected and plotted the data (Figure 18). The team measured salinity at 25 ppt at in the ponded surface water and 35 ppt in the pore water in the sediments. Mr. Branoff also observed black mangrove pneumatophores underwater. This evidence supports the assessment that the mangrove area had been ponded and is not adequately connected to the ocean.

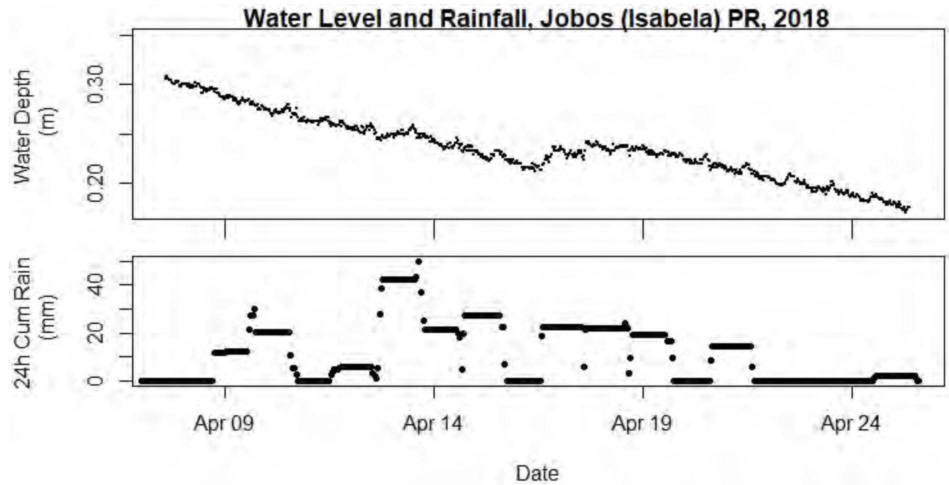


Figure 18: Results of temporary gage correlated with local rainfall

The team noted that the most immediate action that could be taken which would benefit the hydraulic connectivity is to **remove the deposition that is under the foot bridges**. The original conveyance under the bridges could be restored with hand tools. While this would be an improvement, the team made some quick survey measurements while in the field and determined that the beach between the bridges and the ocean appears to be at an elevation that would not allow for the connectivity that the area likely had in the past. Excavating the deposition under the bridges would be an improvement but is unlikely to be sufficient.

The team proposes that the area could also be restored by **reestablishing a channel through the bridges to the ocean.** The most appropriate bridge opening is located approximate location N 18-30.833 W 67-02.983. It is near the center of the mangrove wetland, closest to the ocean, and does not appear to have any dunes or significant vegetation between it and the ocean. The team was also able to observe geomorphic evidence of ponding and potential channel between it and the ocean. Photographs of the potential area for a reestablished channel are shown in Figure 19. This area was surveyed, and an approximate channel alignment was discussed. Excavation to a pre-storm elevation would be necessary. However, the team noted that this would not be to a low tide elevation. The team conducted a quick, concept design in the field and estimated the total length of the proposed channel to be approximately 600 feet with a sinuosity of 1.25. The excavated channel would be 10 feet wide and 2 feet deep. Further analysis is suggested that would make use of stable analogs and especially mapping of pre-storm channel conditions. An aerial map of the site is shown in Figure 20.

Regardless if the treatment is excavation of the deposition under the bridges or a constructed channel, a specific O&M plan should be developed for the site. Debris from the dead woody material as well as sediments pushed by storms can alter the hydraulic connectivity. To reduce the potential for a repeat of the ponding induced impacts to the site, work will need to be accomplished in site. The team suggests that an **MOU be established with USACE regulatory and other stakeholders to allow future maintenance** as needed.

Figure 19: Photographs of team conducting a survey of remnant channel and ponding areas for possible alignment of channel. The team located and discussed a variety of potential channel alignment configurations that could be constructed.

Figure 20: Google Earth image of Jobos Isabella_site. Impacted mangrove area is shown with brown area. Pins show bridge where easiest connection could be made. Date of image is 11/2017.

The team did note that even with an excavated channel through the bridges, the elevated bike path will limit natural connectivity. This paved path is an important amenity that facilitates public enjoyment of the area. The team suggests that consideration be given to totally **removing the path and replacing it with an elevated boardwalk**. Free flow of water during high flows under the elevated boardwalk would be allowed. The team suggests that composites (wood fiber or plastic) be used for the boardwalk material. Material would need to be selected for UV and heat stability.

Hurricane and large storms have occurred in the past and can be expected to occur again in the future. Regardless of what is done with the bridges and the boardwalk, there is a potential for a significant storm to push up sufficient sands to reduce the hydrologic connectivity of the wetland with the ocean. The team noted that the high areas have mangrove vegetation that appears to be revegetating. The team suggests that action be taken to **increase depth diversity** in the wetland system. Installations such as **fill islands/peninsulas** could be installed. This would increase resilience of the system to prolonged inundation caused by future storm events. The peninsulas could include paths and the islands could include habitat features for birds. Both would increase tourist access and use of the system and be a benefit to the local economy.

<u>Punta Tuna Site:</u> This site was visited on 3 and 5 April. It is located at approximately N 17-59.733 W 65-52.833. The site is an Estuarine Fringe and a Basin wetland type. A coastal dune forested with palms is located adjacent to the beach. In a basin lagoon, behind the dune, is the mangrove wetland. It is in a tourist area and is well used. Trails and ecologically oriented educational signage is present. Luxury hotels/condominium units overlook the mangrove area. A park called Reserva Natural Humedal Punta Tuna with an overlook is maintained at the edge of the wetland area. Photographs on brochures and in the signage, indicate that visitors were able to walk through a lush, well shaded mangrove on their way to a beautiful beach. Photographs from a brochure available at the park are shown in Figure 21.

Figure 21: Photographs of the area from brochures provided at the park. These pictures as well as the photographs on the signage indicate that it had been a healthy mangrove system as well as an attractive area that was well used by tourists

The team was able to meet with a park supervisor (Deogrecia Morales) on 5 April and discuss the recent history of the site. The community in the area had been significantly impacted by the storm. Severely damaged houses were observed around the wetland during the visit and electrical power is not available in the community. Wind has uprooted the many of the mangrove and palm trees. The entire mangrove area as well as portions of the town had been flooded. The palm trees appear to be recovering but the mangroves do not. Photographs of the site at the time of the visit are provided in Figure 22 and 23. An aerial map is provided in Figure 24.

Figure 22: Photographs of the Beach area. Note the palms are recovering. Photo on right shows recently excavated channel area

Figure 23: Photographs of the mangrove area. Note the tree damage.

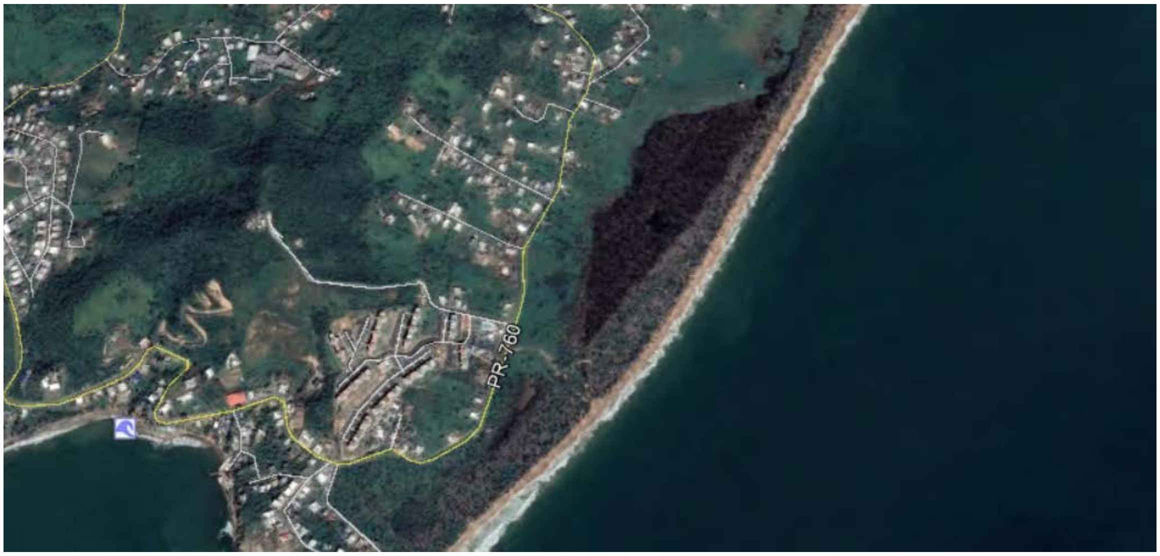


Figure 24: Google Earth image of Punta Tuna site. Impacted mangrove area is shown with brown area. Date of image is 1/2018.

The area had had natural drainage through the beach before the storm. An aerial map showing what the team believes to be this channel is provided in Figure 25. Storm surges had closed the cut and caused an elevated pool in the mangrove area. The team was told that water had also backed up sufficiently to impact some houses in the community, but the team did not directly observe evidence of this situation. The team was also told that local stakeholders had requested permission to reopen the cut but this had been denied by the US Army Corps of Engineers via a phone consultation. As a result, the ponding stayed for four to five months. In addition, as some of the water evaporated, salinity levels were raised.

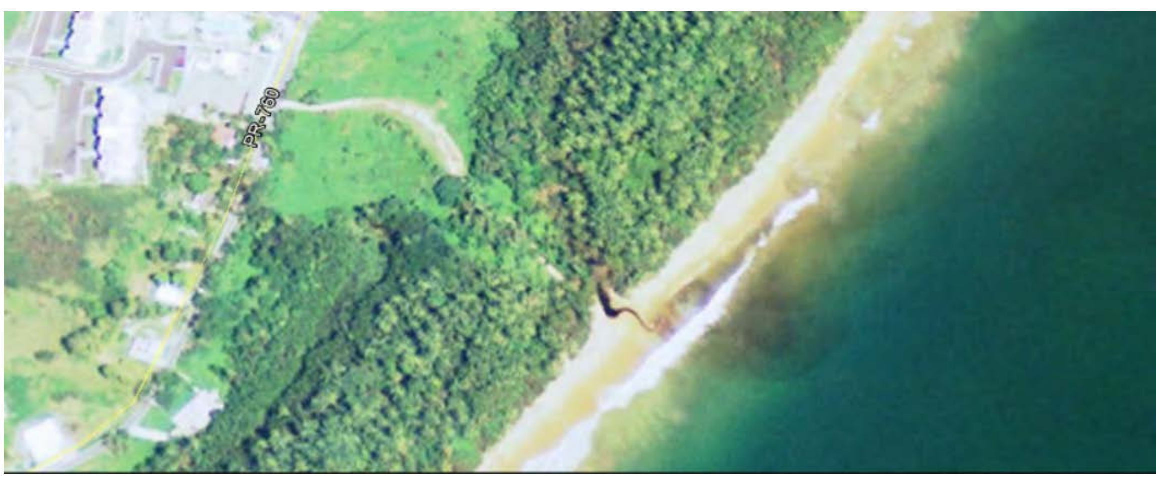


Figure 25: Google Earth image of old exit channel for the Punta Tuna site. Date of image is 10/2004.

The team was informed that when a USACE representative visited the site approximately one month ago, permission was granted to open the channel. The excavated channel is approximately 10 feet wide at the invert, 4-foot-deep, and 20 feet wide at the top. Photographs of the current channel are provided in Figure 26. The water in the mangrove area took 3 weeks to drain.

Figure 26: Photographs of the re excavated channel

At this point, much of the mangroves appear to have been drowned by the prolonged inundation. The team estimated that upwards of 99% of the mangroves appear to be dead. Aesthetics and habitat has been impacted. A photograph is provided in Figure 27. If this mangrove loss is nearly 100%, natural reestablishment will be very slow. **Planting of mangrove seedlings may be necessary to reestablish the system**.

Figure 27: Photograph of the site taken from the Reserva Natural Humedal Punta Tuna. Note condo units at upper right.

The team excavated several auger holes over the course of the two site visits in the re excavated channel. Organic soils were observed a few inches below the surface (Figure 28). The team believe that this indicates that the excavated channel is probably to near the original grade and is suitable. However, the team did discuss that some adjustment in to the channel could be undertaken to improve stability. The team noted that a section that was not recently modified was 32 feet wide at the invert and 65 feet wide at the crest. This may indicate that the currently constructed channel is overly narrow. However, the team did note that such channels in this geomorphic landscape should be expected to be variable and dynamic in section and pattern. Regardless, debris from the wetland (especially due to the large number of dead trees) may clog the channel and additional sands may deposit in the channel during storms. Maintenance is needed to maintain any channel.

Figure 28: Photographs of auger sample in excavated channel

The salinity at the surface of the wetland was measured at 15 ppt during the visit. Pore water was measured at 50+ ppt. It is suspected that the fresher surface water may be perched lenses of a freshwater spring or rainwater. Nitrates and Total Chlorine was measured at zero. Coliform bacteria measured positive and E Coli measures at 4 to 9 colonies per ml. Current water depth is six inches to one foot in the wetland. The depth in the remnant channel under the pedestrian bridge is 1 to 2 feet. The team set an automatic recorder in the wetland near the outlet. The preliminary results are shown in Figure 29. These results are paired with the rainfall in Humacao by Mr. Branoff. The team believes that this information as well as the observed water marks indicates that the current water level in the wetland is near stable.

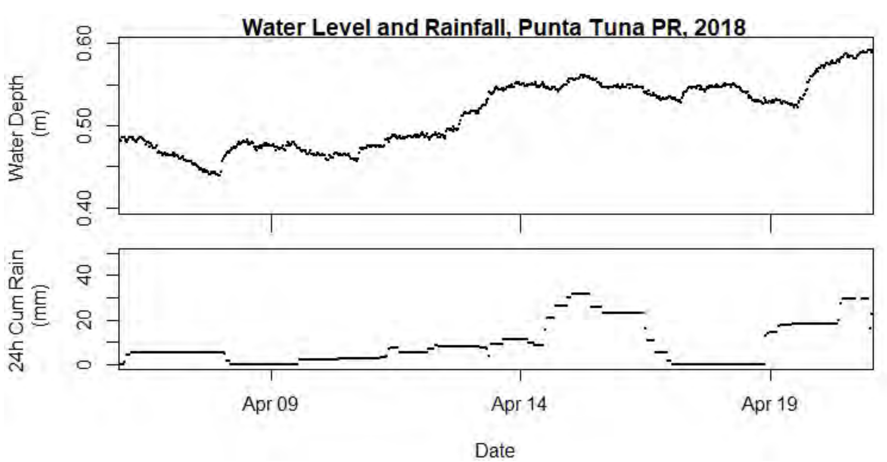


Figure 29: Graph of water levels and rainfall at Punta Tuna

The Punta Tuna mangrove is a valuable amenity for tourism for the area. Recovery has definite economic benefits. The team proposes the following measure to address the current situation.

1- **Remove dead and overhanging limbs** from the pathways to improve public safety.
2- S**ignage should be updated** to describe the storm and the recovery that is being observed.
3- Establish targeted **mangrove planting**
4- The **mangrove area be monitored and studied** as it naturally responds to the storm damage.
5- **Establish an MOU with USACE regulatory and other stakeholders to allow future maintenance of the channel outlet** to be conducted as needed

Punta Santiago Site: This site was visited on the 8th of April. It is located at approximately N 18-10.538 W 65-44.321. The site is an Estuarine Fringe and a Riverine wetland type. An apparently constructed channel passes through the wetland area and under a bridge at the Rt 3 road into the ocean. The team stopped at this bridge and walked upstream into the wetland area. An aerial photograph of the site is provided in Figure 30.

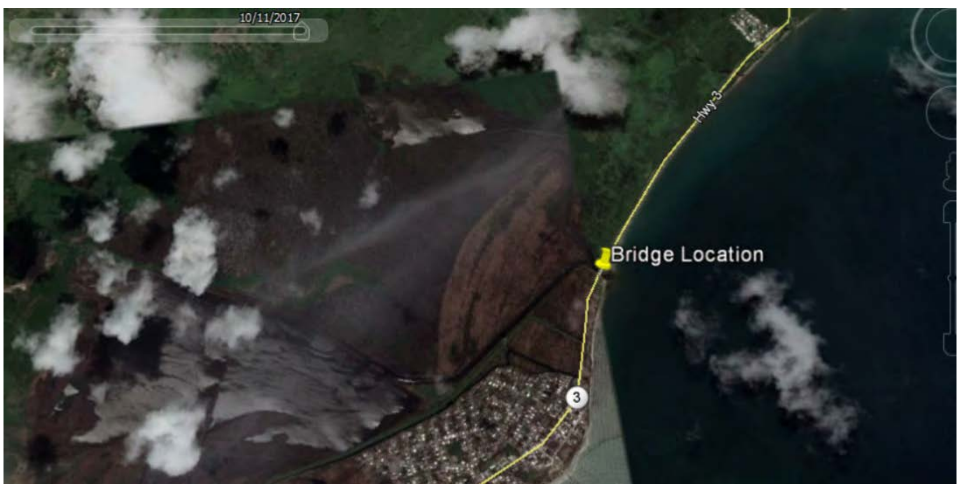


Figure 30: Google Earth image of Punta Santiago site. Date of image is 10/2017

The area was where the Hurricane Maria first made landfall and the damage to infrastructure in the area is significant (Figure 31). The trees in the wetland area show significant wind damage and high-water/debris lines marks indicate that flooding may have been from 3 to 5 feet into the mangrove area. Photographs of the mangrove wetland are provided in Figure 32. However, the bridge opening is apparently sufficient to allow rapid draining of the storm surge and there does not appear to be significant deposition in the mouth of the outlet to restrict hydraulic connectivity. The vegetation appears to be recovering. While large trees were toppled, smaller ones are sprouting. Photographs of the bridge are provided in Figure 33.

Figure 31: Photographs of hurricane impact damage to community.

Figure 32; Photographs of the Punta Santiago_site

Figure 33: Photograph of the bridge

Water quality tests showed total chlorine of 0.5 to 0.6 ppm indicating that there may be impacted infrastructure leaking water in the watershed. However, spot E. coli tests showed lower levels of contamination (1 to 3 colonies per ml) and coliform was negative. Nitrogen contamination showed trace. The bridge does not appear to significantly impact tidal exchange and the salinity measurements in the wetland and in the ocean are the same. Recreational fishing and crabbing were observed in the area.

The team believes that this site exhibits natural and healthy recovery from the storm. While the area looks different than it did pre-storm and is perhaps unattractive, it is recognized that big storms tend to up root and impact the big trees. Younger trees fill in the openings as they are exposed to more sunlight. The current recon study indicates that **no significant restoration or reclamation efforts are necessary**.

SITE RECOMMENDATIONS: Site specific recommendations were identified and discussed for each site. These are summarized in Table 1.

Table 1: Site Recommendations

Site Name	Site Condition	Reclamation Recommendation
Torrecillas/ Pinones	Site has been significantly impacted by wind but the entire understory appears to be recovering naturally	1-Provide signage that describes natural response of mangrove wetland forests to hurricanes 2- Clear overhead dead trees along walking trails and road which may be a hazard to visitors. 3-Monitor plant succession and mangrove recovery

Cucharillas/ Malaria Channel	Significant mangrove loss from storm. Recovery is limited by flooding and lack of seawater exchange due to current condition of pump station/Tide gates	Until Funding /Repair/ Management improvements are made at pump station/ tide gates, work in the mangrove wetland forest should be limited.
Jobos Isabella	Site has been impacted with significant mangrove loss in center but recovering mangroves along edge	1-Remove deposition under bike train bridges and improve outlet with a constructed channel 2- Establish an MOU with USACE regulatory and other stakeholders to allow future maintenance of the channel outlet to be conducted as needed 3- Install fill islands/peninsulas for depth diversity to increase resilience 4-Replace fill portion of bike path with elevated trail 5-Monitor plant succession and mangrove recovery
Punta Tuna	Site has been impacted with nearly 99% mangrove loss.	1-Improve outlet from wetland system to ocean (maintenance will be needed) 2- Establish an MOU with USACE regulatory and other stakeholders to allow future maintenance of the channel outlet to be conducted as needed 3-Planting of mangrove species 4-Clear overhead dead trees along walking trails which may be a hazard to visitors. 5- Monitor plant succession and mangrove recovery
Punta Santiago	Site has been impacted but is recovering naturally.	Do Nothing

APPRECIATION: The undersigned would like to acknowledge and thank the Puerto Rico NRCS staff and the University of Puerto Rico – Rio Piedras for an informative and enjoyable visit.

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