Natural Infrastructure Restoration to Enhance Climate Resilience in Puerto Rico

2019 North American Partnership for Environmental Community Action (NAPECA)

The Ocean Foundation

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FollowUp Form

Project Title*

Natural Infrastructure Restoration to Enhance Climate Resilience in Puerto Rico

Quick Analysis

1) What was the single best thing that happened during the project?*

Through this project, we were able to successfully (and cost-effectively) develop a large-scale feasibility assessment and restoration plan for the eastern portion of Jobos Bay (up to 695 acres). This is a remarkable accomplishment given this will be among the largest mangrove restoration projects ever attempted in the Caribbean (and the largest in Puerto Rico). If all goes as planned and we are able to secure significant financing over the next five years (+US$1 million), we should also be able to make this the very first certified mangrove restoration project under REDD+ in Puerto Rico. This large-scale project will become an important case study and training site for resource managers and restoration practitioners throughout the Caribbean in the decades to come. By pioneering new methods in a large-scale context, we can encourage other projects to scale up and pursue more challenging restoration goals. This will be critical as countries in this region pursue new nature-based pathways to meeting their Nationally Determined Contributions (NDCs) under the Paris Agreement. Pursuing larger scale habitat restoration projects will also unlock new sources of financing through the carbon market given the vast majority of blue carbon projects completed to-date either are too small or lack sufficient resources to pursue expensive third-party verification.

2) What was the single worst thing that happened during the project?*

The COVID-19 pandemic was the single worst thing that happened given it resulted in significant delays and cost overruns. For much of the second half of the project period, the Jobos Bay National Estuarine Research Reserve (the project site) was closed and its staff (DNER) were prevented from providing any support. Given the quarantines and mandatory curfews, it was very challenging to conduct the research and detailed studies needed in order to create the feasibility assessment and restoration plan. This further complicated our financial situation because it required additional trips due to time constraints and limited availability. In addition, our inability to work with the DNER and the Reserve staff for much of the feasibility assessment resulted in us having to hire additional consultants at greater cost than originally anticipated. While the situation improved towards the end of the project period as some restrictions were relaxed, we are still being challenged by the pandemic as we enter the next phase of the project.

3) What was the single most unexpected thing that happened during the project?*

The size of the potential restoration area is very unexpected given we had anticipated identifying 100-200 acres that are feasible for restoration. Our finished restoration plan, which includes up to 695 acres, will allow us to seek significant financing through blue carbon offsets and may make it cost-effective for certification under Verified Carbon Standard (VCS). Furthermore, we were surprised to discover that the restoration cost will be significantly less than expected given that it is unlikely that we will have to remove or modify any surrounding roads (which can cost tens of millions of dollars). While the project will require expensive equipment and some major earth-moving activities, we should be able to leverage existing partner resources and personnel support to significantly reduce costs from design and implementation to long-term monitoring. The size of the project also makes us eligible for much larger funding sources, and we are actively pursuing support from the Green Climate Fund, FEMA, and the U.S. EPA.

4) What was the single thing that could have been done to make the project more effective?*

We experienced significant challenges identifying people outside of our consultants to assist with work at certain points during the project. While much of this can be attributed to COVID-19, a few of the key trips could have used additional planning to ensure sufficient personnel were available (especially for manual labor-intensive activities like mangrove propagule transportation and planting). Specifically, involving more outside researchers and scientists during the intensive field work portion associated with the feasibility assessment could have proved very beneficial in the long-term for capacity building reasons. Although bringing untrained personnel into the field poses challenges and can significantly delay the speed of work, the experience is useful and hard to replicate in a workshop. In the future, we will allocate additional time and resources to ensure more people can be involved in the most technical aspects of the project.

5) What will happen as a result of this project during the next five years?*

Following the approval of our permit (anticipated in summer of 2021), we will engage in a major fundraising campaign to support large-scale restoration efforts and future workshops. We anticipate the project cost to exceed US$1 million over the next five years. In order to finance this project, we intend to pursue formal certification of the project under VCS's REDD+ methodology in addition to seeking support for natural infrastructure improvements and hurricane recovery (given much of the damage is hurricane-related). We will also pursue larger grants through government and private foundation sources.

We anticipate that on account of our initial restoration efforts and training, we will be able to help support the Jobos Bay National Estuarine Research Reserve in directly securing additional federal funding to expand its own programming. The Reserve is gaining more attention through these preliminary seagrass and mangrove restoration efforts, and we hope to leverage our success to-date to help Reserve staff raise more funding to better meet their growing personnel, equipment, and monitoring costs. We intend to continue to introduce new technologies and training that will build local expertise and support the long-term protection of the Reserve and its rich biodiversity.

6) Is there anything else that is important to say about the project?*

We cannot emphasize enough the incredible momentum that has resulted from the CEC's support of our project. Arriving at a critical juncture, and despite the global COVID-19 pandemic, the mangrove project feasibility assessment and restoration plan is paving a path to a massive effort in Jobos Bay in the near future. Not only will this elevate the status of the Reserve, but it will represent The Ocean Foundation's single biggest blue carbon restoration project to-date. We are confident that large scale efforts like this will unlock new financing opportunities in the carbon market given the interest we have already been able to generate through this project. We know that this project can serve as a real-world demonstration of the strategies and techniques involved in landscape-scale coastal habitat restoration. And, it will surely catalyze others in the region to pursue the same.

Project Evaluation

Results of the monitoring and evaluation activities*

As detailed in our workplan, here is our performance related to Objectives #1, #2, and #3:

Mangrove Restoration
# of acres restored: 1 (goal: 1-2)
# of acres of stabilized forest adjacent to restoration sites: 2 (goal: 2-3)
# of propagules / transplants collected / cultivated: 510 (goal: 500)
# of field days: 42 (goal: 14)
# of volunteers: 24 (goal: 10)
# of paid laborers: 7 (goal: 5)
% mortality after 6 months: 7% (goal: less than 25%)

Long-Term Monitoring Workshop
# of participants: 40 (goal: 25)
# of government agencies represented: 2 (goal: 3)
% male v. female: 38% male, 62% female (goal: 50% - 50%)
% minority: 80% (goal: 75%)

Large-Scale Mangrove Project Feasibility Assessment / Restoration Plan
# of acres assessed for mangrove restoration: 983 (goal: 600)
# of acres identified for mangrove restoration: 695 (goal: 100)
# of government agencies directly engaged in project scoping: 2 (goal: 3)
# of volunteer Puerto Rican researchers participating: 24 (goal: 5)
# of paid Puerto Rican researchers participating: 4 (goal: 3)
# of field days: 40 (goal: 28)

In addition to these metrics, we also administered a post-workshop survey to all of the participants. Of the 12 respondents, the results were overwhelmingly positive. Although we were disappointed by the turnout for the survey, the low participation is understandable given that the COVID-19 pandemic quarantines across the United States were implemented in the week immediately following the workshop.

Project Summary - Part I. Description

Participating organizations and geographic location(s) of the project (a small map can be included*

The Jobos Bay National Estuarine Research Reserve (JBNERR) is a federally protected estuary located in the municipalities of Salinas and Guayama in the southern part of Puerto Rico. The 2817-acre reserve contains five distinct habitat types and provides sanctuary to endangered species including the brown pelican, peregrine falcon, hawksbill sea turtle, green sea turtle, several species of shark, and the West Indian manatee.

During this project, we worked closely with the Puerto Rico Department of Natural and Environmental Resources (DNER), which co-manages the reserve alongside JBNERR staff. In addition, Merello Marine Consulting, LLC provided technical services, including project design, permitting, implementation, and training workshops. In the project period, we hosted a long-term monitoring workshop that included 40 participants from across Puerto Rico including the University of Puerto Rico, the Vieques Conservation and Historical Trust, and FEMA.

In addition to the workshop activities, Peak Design (another project funder and gear sponsor) and the Commission on Environmental Cooperation (CEC) also donated their time and resources to document the training. The CEC-contracted filmmaker shot several interviews with workshop participants and Reserve staff. We also brought the filmmaker into the field to gather b-roll for the CEC video.

A one paragraph background or problem statement (why was the project carried out?)*

In 2017, the Jobos Bay National Estuarine Research Reserve's mangrove forests were heavily damaged by Hurricanes Irma and Maria as a result of vessel groundings that occurred due to extreme wave and wind action. Through human intervention and targeted restoration activities, the rate of recovery in damaged mangrove forests can be dramatically increased thereby minimizing wider impacts to the environment and surrounding communities. After conducting a series of planning visits in 2019, a pilot project restoration plan was developed in which areas were prioritized based on a post-hurricane disturbance assessment released in July 2018 by NOAA for the Federal Emergency Management Agency (FEMA). Through this project we intended both to restore a 1-acre section of mangroves destroyed during the hurricanes and identify additional large-scale sites (+200 acres) that exist on the eastern edge of the Reserve (Aguirre State Forest) that require comprehensive assessment and restoration planning. This project also identified a need for a long-term monitoring training workshop to better equip our local partners with the skills and expertise to assess the mangrove restoration expansion sites and determine the efficacy of the project once completed.

A one-paragraph general description of the project (what was done?)*

The main objective of the project was to develop a large-scale mangrove restoration plan for the eastern portion of Jobos Bay. We assessed 983 acres for mangrove restoration feasibility, and a total of 695 acres were identified for our restoration plan (see attached). This project will represent one of the largest of its kind in the Caribbean. We have submitted our permit application to the Army Corp of Engineers, and we hope to receive approval to move forward sometime in the summer of 2021. In addition to the large-scale restoration plan, we also restored 1 acre of mangroves that were destroyed in 2017 by hurricane-related impacts. Finally, we conducted a four-day training workshop on seagrass and mangrove long-term monitoring for 40 participants in March 2020 at the Jobos Bay National Estuarine Research Reserve. Two days were lecture-based and two days were field-based at our established seagrass and mangrove restoration sites. Participants learned sophisticated long-term monitoring techniques and how to use advanced monitoring equipment to help measure the effectiveness of restoration efforts.

A one-paragraph description of outcomes and follow-up (what did the project achieve?*

The large-scale mangrove restoration project designed through this project will represent one of the largest of its kind in the Caribbean. We assessed 983 acres for mangrove restoration feasibility, and a total of 695 acres were identified for our restoration plan (see attached). We have submitted our permit application to the Army Corp of Engineers, and we hope to receive approval to move forward sometime in the summer of 2021. Our other achievements include the completed restoration of 1 acre of mangroves at our pilot site with significant volunteer support as well as the long-term monitoring workshop. The large turnout and broad geographic diversity of our participants exceeded our expectations, both for the workshop and the restoration activities. We are confident that the skills and experience provided by this project will help catalyze other habitat restoration projects across Puerto Rico.

Project Summary - Part II. Analysis

Successes*

The project’s most significant success was the development of a feasibility assessment and restoration plan for the expanded mangrove restoration site on the eastern side of Jobos Bay (695 acres). This area will provide greater protection for vulnerable coastal communities and critical power-generating infrastructure in the area. Local partners have participated in all stages of site assessment, field activities, hydrological modeling, restoration planning, and permitting. This effort included conducting detailed investigations of the community ecology and structure of the naturally occurring mangrove species at the expanded project site, in particular the patterns of reproduction, distribution, and successful seedling establishment. We performed a comprehensive assessment of the modifications of the mangrove environment that occurred as a result of past hydrological modification and that currently prevent natural secondary succession. This allowed us to develop an expanded mangrove restoration plan for which we have submitted a joint permit application to the Army Corps of Engineers in collaboration with the DNER.

Challenges*

The most significant challenge encountered during the project was the COVID-19 pandemic. Not only did this have a negative effect on participation at the long-term monitoring workshop, but it also resulted temporary closures of the Jobos Bay National Estuarine Research Reserve. Our key partner, the Puerto Rico Department of Environmental and Natural Resources, was also restricted from going out into the field and providing material, equipment, and labor support for long periods of time. These challenges resulted in significant delays in the restoration work and feasibility studies. Furthermore, it limited the number of staff available to us, which required us to hire additional support. While we were able to eventually overcome these issues, there are still tight restrictions associated with visitation, which continues to challenge our ongoing efforts as we move towards the large-scale restoration work.

Lessons Learned*

We encountered a few challenges with workshop logistics that we intend to better prepare for next time. Most significantly, we had issues securing enough boats for the seagrass field portion due to a last-minute scheduling conflict with the DNER (i.e. they had their patrol boat at a different marina). Although we were able to adapt with the small vessel at the Reserve, it created time constraints on the field day. Next time, we intend to charter a local vessel to ensure we can host at full capacity in the contingency that our partner vessels are unavailable.

Another lesson learned relates to timing. Like the previous year, we scheduled the field portion of the mangrove portion during the day. However, given the tropical climate, it is inadvisable to work out in the field during peak hours. We experienced an exceptionally hot day in the field this year. One participant experienced dehydration and heat sickness. Next time, we will schedule any mangrove field excursions in the early AM and late PM hours (and insert classroom time in-between to facilitate lunch).

What next?*

Following approval of our new permit, we intend to conduct a major fundraising campaign to raise the significant capital needed to execute such a large habitat restoration project (up to 695 acres of mangroves). We anticipate the effort to cost in excess of US$1 million depending on the types of interventions we decide to implement. Unlike smaller scale projects which require large amounts of manual planting, much of the work for this project will focus on hydrological manipulations, including digging canals to promote the flow of water, cleaning brush and debris from culverts, and planting mangrove “islands” that will propagate naturally while building up land for expanded colonization. This effort will require multiple organizations and dozens of resource managers, biologists, and restoration engineers as part of our team. We hope to certify this project under REDD+ through the Verified Carbon Standard (VCS) in the future. Certification will require significant resources and negotiation with the U.S. federal government regarding carbon credit rights generated on land owned by NOAA.

In addition, we intend to continue our training and capacity building efforts through future workshops at the Reserve headquarters post-pandemic. We are also seeking an amendment to our existing pilot project permit that will allow us to complete up to 100 acres of seagrass restoration in Jobos Bay, which will be pursued both for carbon offsetting and training purposes. One overarching goal is to secure funding for expanded long-term monitoring efforts, both at our restoration sites and more broadly throughout the Reserve.

Financial Report

Financial Report*

Financial-Report-Final-May - December 2020.xls
See attached (in USD).

Project Products

Mangrove Feasibility Report_11012020 - lo-res.pdf

See attached for the large-scale mangrove project feasibility assessment and restoration plan. Confidential / not available for the general public.

File Attachment Summary

Applicant File Uploads

- Financial-Report-Final-May - December 2020.xls
- Mangrove Feasibility Report_11012020 - lo-res.pdf

Financial Report (USD)

Project Budget for: The Ocean Foundation
Project Name: Natural Infrastructure Restoration to Enhance Climate Resilience in Puerto Rico

PART I. FOR THE LAST PAYMENT PERIOD OF MAY 2020 TO DECEMBER 2020

	Current amount (US$)	Cumulative amount to date (US$)
Advance payment received from the Commission	$ 28,624.74	$ 88,863.90
Expenses		
Salaries & Benefits	$ 1,700.00	$ 23,700.00
Equipment and Supplies	$ 14,438.51	$ 24,438.51
Travel	$ 2,700.87	$ 11,952.26
Consultants/Professional Fees (if applicable)	$ 27,700.00	$ 48,200.00
Overhead (not to exceed 15 percent)	*$ 5,724.95*	$ 12,586.22
Other (itemize on sheet 'Other')	$ -	$ -
Total Expenses:	**$ 52,264.33**	**$ 120,876.99**
Balance (cumulative advance payment less total expenses)	**$ (23,639.59)**	**$ (32,013.09)**

Part II. Total cost of the project

Total contributions	**Total**
Contribution from the Commission (CEC)	$ 118,796.16
Contribution from 11th Hour Racing	$ 50,000.00
Contribution from JetBlue Airways	$ 50,000.00
Contribution from Bernard & Norton Wolf Family Foundation	$ 30,000.00
Contribution from Promise of Hope Foundation	$ 9,619.37
Contribution from EVDEMON Partners International	$ 1,500.00
Total cost	$ 259,915.53

Notes:

- Please specify whether report is submitted in **Canadian dollars**, **US dollars** or **Mexican pesos**
- Budget categories may vary according to your original budget
- It is not necessary to enclose receipts (but they should be retained in case of audit).

Project Budget for: Enter Organization Name

Project Name:

PART I.

Other Expenses		Current amount ($)	Cumulative amount to date ($)
Item 1			
Item 2			
Item 3			
Item 4			
Item 5			
Item 6			
	Total Other Expenses:	$ -	$ -

PART II. TOTAL PROJECTED DISBURSEMENTS - PAY PERIOD (

Other expenses		Projections ($)
Item 1		
Item 2		
Item 3		
Item 4		
Item 5		
Item 6		
	Total projected disbursements	$ -

“Assessing Jobos Bay and Aguirre Park (Puerto Rico) mangrove wetlands extension, shoreline condition and rehabilitation/restoration feasibility after Hurricanes Maria and Irma impacts (2017)”

DRNA/ JBNERR
In collaboration with
The Ocean Foundation
Merello Marine Consulting

September 16, 2020

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I. INTRODUCTION and BACKGROUND

The Jobos Bay National Estuarine Research Reserve (JBNERR) is a federally protected lagoonal estuary located in the municipalities of Salinas and Guayama on the south-central coast of Puerto Rico (Fig. 1). The 2883-acre reserve encompasses a tropical marine ecosystem composed of mangrove forests, seagrass meadows, coral reefs, and macroalgae communities. The reserve provides sanctuary and essential resources for fish and wildlife including endangered species such as the brown pelican, peregrine falcon, hawksbill, green sea turtles, manatees and several species of sharks. In 2017, Hurricanes Irma (September 2, 2017) and Maria (September 20, 2017) impacted this region of Puerto Rico resulting in many casualties, complete loss of power, and significant physical and biological disturbance to Jobos Bay. In July 2018, NOAA released a report identifying JBNERR's seagrass and mangrove forests, both key habitats and sources of valuable ecosystem services, as negatively impacted by the storms.

Based on that initial assessment, the overall goal of this project is to develop and implement a rehabilitation/restoration (sensuField 1998) plan for damaged and impacted mangrove wetlands in the JBNERR. Accelerating and enhancing the natural recovery of mangrove wetlands will offset the observed net mangrove area loss as result of the combined impact of hurricanes in 2017 and past cumulative-long term negative impacts (e.g., hydrological alterations associated to land use/change) within and around the JBNERR. Thus, a comprehensive assessment and evaluation of the extension of the current damage will help to ameliorate, for example, potential carbon emissions and rehabilitate and improve natural wetland regeneration and natural resilience in this coastal region. Rehabilitation and restoration measures of mangrove habitats will also contribute to the health and maintenance of surrounding seagrass and coral reefs and species diversity that depend upon their ecological connectivity with seagrass meadows, including local human communities economically and environmentally tethered to the productivity and sustainability of these valuable ecosystems.

Mangroves and seagrasses are recognized worldwide as foundation species and one of the most productive and diverse coastal marine communities in the world (Rivera-Monroy et al. 2017)(Orth et al. 2006). In tropical western Atlantic ecosystems, like Jobos Bay, widely distributed mangrove wetlands are composed primarily of four species; red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*), white mangrove (*Laguncularia racemosa*) and button wood (*Conocarpus erectus*). All four species deliver a wide range of valuable ecosystem services (Lopez-Portillo et al. 2017, Ochoa-Gomez et al. 2018). These services include functions such as nurseries, shelter and food for juvenile fish, invertebrates, avifauna and a diversity of vertebrate species (Lee et al. 2014, Himes-Cornell et al. 2018a, Himes-Cornell et al. 2018b). Mangroves also stabilize sediments and attenuate wave energy; protecting shorelines from erosion and maintaining water clarity in the Bay. Along with high rates of nutrient cycling associated with high primary production and carbon storage in plant biomass and soils, mangrove habitats are also responsible for maintaining water quality conditions (Kristensen et al. 2017, Rivera-Monroy et al. 2017, Osland et al. 2018). Positive feedbacks made possible by many of these services contribute to the long-term persistence of tropical mangrove forest and the overall resiliency of coastal ecosystems (Rivera-Monroy et al. 2019). Interruption of these positive feedback mechanisms by human and/or natural disturbance can alter the quantity and quality of valuable ecosystem services provided by mangrove and seagrass.

Hurricanes are natural recurring events frequently encountered in the western Atlantic and Caribbean tropical coastal ecosystems that can have significant and long-lasting bio-physical positive and negative impacts on coastal wetlands, including mangroves (Castañeda-Moya et al. 2010, Danielson et al. 2017, Rivera-Monroy et al. 2019, Simard et al. 2019). A preliminary assessment indicated that the extraordinary severity of two consecutive storms in the 2017 hurricane season inflicted damage to the mangrove forest structure properties throughout Puerto Rico, including mangrove habitats in Jobos Bay as a result of Hurricane Maria wind velocity and strength (NOAA 2018). Wave energy (turbulence and currents) associated with hurricane force winds and storm surge eroded some portions of the fringe mangrove forest. Moreover, as a result of the storm surge many vessels were grounded on top of the mangrove trees creating significant localized destruction, including decimation of small mangrove islands. Following the storm, water clarity in the Bay was severely impaired by re-suspended sediments (e.g., increasing turbidity) and the additional release of sediments and nutrients discharged by storm water from the surrounding watersheds. Many of the mangrove forests are still impacted from debris deposited on top of surviving mangrove trees. Some of the eroded sediments were also re-deposited, burying portions of sub-tidal and intertidal seagrass beds. The cumulative effects of all these factors significantly challenged the inherent resilience of the mangrove ecosystem by acutely impacting primary productivity, net growth, reproduction and regeneration.

While tropical mangrove forests can naturally regenerate from a disturbance given the appropriate environmental conditions (e.g., relative elevation, hydrology, hydroperiod, pore water salinity), the time needed for natural regeneration after disturbance may slow the rate of regrowth resulting in substantial short- and long-term disruption to the local ecosystem functional properties and its biological productivity, especially under the risk of another potential landscape-level disturbance.

Vessel grounding injuries and hurricane impacts to fringing mangroves structure share several physical and biological characteristics. Whereas natural disturbances from seasonal winds and tides can cause gaps along berms where fringe mangrove forest form a fringing “barrier” or boundary with tidal flats or basin forests, hurricane force winds and vessel groundings cause cumulatively unstable margins due to erosion and sediment re-distribution. This impact can weaken the root system making the mangrove margin unstable and susceptible to further berm erosion (Krauss et al. 2003, Krauss et al. 2006). The compounded effect of gap creation along the berm and persistence of high energy winds and tides can significantly impact the integrity of the injured vegetation, diminishing the capacity of the surrounding forest to re-grow into the unvegetated extensive openings caused by the storms as currently observed in the JBNERR as result of hurricanes Maria and Irma. Therefore, damaged mangrove forests rate of recovery can be significantly increased by implementing restoration and rehabilitation activities that minimize a long-term impact on avian and marine organism density and life cycle and other ecological services provided by mangrove dominated habitats. In addition, mangrove wetlands can significantly improve local water quality and trap sediments to reduce erosion; this sediment reduction input into adjacent estuarine waters can also protect seagrass, and coral reefs by reducing both turbidity and transport suspended solids enhancing natural regeneration of these already stressed habitats due to other processes caused by climate change, variability and human impacts. Indeed, coral reefs, which also serve as important habitat and a source of food, benefit from the presence of healthy, expansive seagrass beds as part of an interdependent and ecologically connected coastal ecosystem.

The current scope of this project capitalizes on previous risk and vulnerability assessments and local coastal planning programs performed to date in and around the JBNERR.

These initiatives include NOAA's estuarine reserve profile where a comprehensive assessment and restoration-related recommendations are listed to improve the health and resiliency of JBNERR coastal ecosystem; this evaluation also underscores the post-hurricane disturbance assessment released in July 2018 (NOAA 2018). This project will advance: a) the region's resilience goals through the reduction of storm surge impacts; b) conservation goals through the creation and restoration of habitats for native species; c) the community's goal to protect critical power-generating assets. The proposed restoration project will work closely with the Puerto Rico Department of Natural Resources (PRDNR) through its Environmental Program to achieve the department's strategy in restoring and improving habitats of ecological and economic importance within the JBNERR.

II. OBJECTIVE

To acquire critical mangrove forest structure baseline data and information to conduct and produce a feasibility study to develop a mangrove rehabilitation/restoration program.

III. RATIONALE -LANDSCAPE FEASIBILITY

The objective of this landscape feasibility study is to identify current disturbed, deforested, or die-back zones in mangrove wetlands in four areas located in the Jobos Bay and Aguirre estuaries as a result of Hurricane Maria's impact in 2017 (**Figure 1a**). Although the mangrove area is currently undergoing natural succession and potential recovery in some park regions after 3 years, there is no actual data and information to assess the extension and recovery rate at local scales. Previous observations indicate low recovery in some sectors due to previous environmental conditions (e.g., hypersalinity, hydrological alterations and road construction). As part of the initial management and conservation goals (Jobos Bay Management plan, https://coast.noaa.gov/nerrs/), it is increasingly necessary to produce baseline data and determine the current status of areas where mangrove mortality was high as a result of Hurricane Maria, including areas that were impacted but that mortality was already occurring. This initial information should be acquired to develop management and rehabilitation/restoration (sensu Field 1996) plans to determine both potential recovery trajectories and habitat shifts where mangrove vegetation areas can be replaced by non-mangrove vegetation (e.g. dune/saline). Since Hurricane Maria landed as a cat-4 (155 miles/hour), approximately 41 km (Puerto Yabucoa) from Jobos Bay (Cartier 2019), there were significant changes in the forest structure through defoliation, tree snapping, and uprooting, which in turn influenced species composition, successional patterns, nutrient cycling, tree mortality, and potential loss in soil elevation. Thus, there is a wide impact gradient that needs to be defined to forecast forest and habitat recovery at mid (5-6 years) and long term (decadal) temporal scales.

The degree of Hurricane Maria's impact on the Jobos Bay mangroves was related to physical conditions of the storm (i.e., intensity, wind velocity, size) and the proximity of mangrove wetlands to the hurricane's path. Yet, currently there is no extensive ground-truthing to evaluate these conditions in the complex canals/embayment systems to determine damage and the degree of resilience and resistance to future changes in mangrove extension, structure and productivity within the park boundaries. This is a major priority due to changes in hydrology in channels and embayments where an altered hydroperiod can hinder forest recovery as a result of, for example, sediment deposition/transport and erosion. In fact, some of these areas have been cumulatively impacted by road construction, agriculture and infrastructure development even before Hurricane Maria impacted this region.

Overall, this information is needed to compare “before hurricane-impact” forest structure conditions and thus determine recovery trajectories, including functional properties as carbon storage/sequestration, water quality, and habitat for fisheries. One of the major concerns is the area’s net loss as a result of the tropical storm. Although there are already studies determining overall mangrove mortality rates as of a result of Hurricane Maria in the North and Southern Puerto Rico coastal regions (Branoff et al 2018), further work is needed to establish specific and representative long-term monitoring locations within the Park to determine how mangroves net area, and associated ecosystem services, will change within the next decade. Previous studies in the Gulf of Mexico and the Caribbean show that hurricane impact causing more than 90% canopy defoliation and/or <10% tree mortality in mangrove wetlands can return to previous forest structure condition within 6 years (Danielson et al 2018, Rivera-Monroy et al 2019)

Further, acquiring current forest mortality spatial extension and hydrological/hydroperiod alterations around and within the JBNERR is essential to evaluate future cumulative hurricane impacts since it is assumed that tropical cyclones events will increase in frequency and strength across the Caribbean Region (Emanuel 2013). As sea levels rise and hurricane impacts increase, potentially impacting JOBOS Bay, it is necessary to determine how this natural disturbance interaction at large spatial scales will affect mangrove forests structural and functional properties. Therefore, both mitigation and adaptation measures need to be developed and implemented to advance the Jobos Bay management program, including the conservation of mangrove wetlands.

IV. METHOLOLOGY APPLICABILITY

The following ‘applicability conditions’ need to be met to use the methodology for a potential project in mangrove-dominated areas of Jobos Bay characterized by high mangrove mortality:

1. Evaluating the degree of mangrove forest canopy damage/recovery/ extension under different hydrological conditions across the park,
2. Identify Project activities to restore hydroperiod; project activities potentially include removing barriers and restoring tidal flows in wetlands and associated tidal channels,
3. Assessing afforestation/reforestation/re-vegetation activities (enhancing natural regeneration) in combination with restorations of hydrological conditions,
4. Determining potential eco-engineering activities to restore flooding and hydrological connectivity and their maintenance in the long term.

V. PROJECT ACTIVITIES

The overall project will include the following key steps and activities:

1. Evaluation Mangrove forest structure and species assemblage/dominance,
2. Production of GIS mapping/Aerial image data
3. Recommending forest monitoring areas (circular/rectangular),
4. Evaluating state of degradation/mortality and canopy recovery in key areas under different hydrological regimes (fringe and basin zones),
5. Evaluation of salinity regime and distribution (water column and soil porewater),
6. Assessing relative elevation associated with forest recovery,
7. Assessing existing and current hydroperiod data to evaluate the potential application of a mangrove-mass balance hydrological model to forecast porewater salinity,

8. Assessing of existing mangrove forest structure to project forest recovery (forest demographic model),
9. Long term analysis of climate variables to validate/calibrate mangrove mass balance model.

VI. MANGROVE RESTORATION FEASIBILITY SITE SELECTION PROTOCOL

The selection of candidate restoration sites utilized a three-tier process. Initial site selection conducted in tier 1 incorporated a geo-spatial analysis based on NOAA's rapid assessment of Hurricane's Irma and Maria's impacts in Jobos Bay during 2017 (NOAA 2018). The NOAA assessment included a review of pre- and post-hurricane high resolution satellite and aerial imagery focused on identifying and locating key indicators of broad-scale disturbance. In order to identify potential hurricane damage in Jobos Bay, and Aguirre Park (state park located adjacent to Jobos Bay) at a higher resolution, the second tier of our evaluation relied on additional detailed interpretation of imagery by the non-profit organization The Ocean foundation. This assessment focused on a specific set of candidate sites in Jobos Bay and at the adjacent park Parque de Aguirre that were identified in a comparison of pre- and post-storm imagery. Where possible, we also used the same imagery to identify potential mangrove sites negatively impact by vessel landings due to storm surge (henceforth, vessel injury sites) including damage incurred to mangrove structure due to vessel initial damage and cleaning/removal activities. The polygons of suspected hurricane related damage produced by NOAA were compiled and inspected in ARC GIS and then compared in order to develop a final list of **4 candidate sites** for field inspection (**Figure 2**).

To verify the interpreted images, Tier 3 field inspections of the 4 zones were conducted between January 28 – January 30, 2018 by staff from Merello Marine and The Ocean Foundation. A second field inspection was conducted between March 7 – March 8, 2020 (Merello Marine in collaboration with Dr. Victor Rivera-Monroy (LSU)). The feasibility study survey of the 4 zones was completed between July and August 2020.

All four sites were assessed for mangrove species composition, water depth, tide stage, wave exposure, general current spatial patterns, salinity, pH., temperature, relative elevation, mangrove physiognomy, qualitative sediment composition, and damage/injury type. Most of the injury features we assessed were in mangrove forests dominated by the mangrove species *Avicennia germinans* (black mangrove) and *Rhizophora mangle* (red mangrove). Damages to the mangrove forest structure was categorized as either direct hurricane impact or post hurricane secondary damage, and vessel impact (due to hurricane winds), or in some cases, a combination of these three impacts. Hurricane related impacts were identified as either mangrove forest partial to complete deforestation, anoxic conditions due to water accumulation (stagnant water) or blowout features, or by areas were the mangrove was either excavated or buried by sediments that were assumed to be redistributed during the storms. These types of injuries to the forest include gap forming disturbances and excavated uprooted impact that increases vulnerability to expanding erosion. This erosional force can be potentially augmented during future storm events and energy winds with further loss in elevation (e.g., berms). Hydrological restoration of these areas is critical to enhance natural regeneration and implement small-scale targeted reforestation activities to accelerate the development of the mangrove forest structure (i.e., tree density, propagule sources) and aboveground/belowground biomass.

VII. FEASIBILITY STUDY SITES

During Tier 3 site selection, **four mangrove forest sites were selected for the feasibility study: Sites A, B, C, and D.** (**Figure 2**).

Site A: Site A is a 100-hectare mangrove forest located in the municipality of Aguirre within the boundaries of the State Park Bosque de Aguirre.

This mangrove forest was heavily damaged by the combined impact of Hurricanes Irma and Maria. During and after the storms, the sediment was partially redistributed due to the lack of belowground biomass/root system as result of previous disturbances. Thus, sediment retention was low altering the natural drainage and local hydrology (**Figure A**). **Site A** is approximately **100.8-hectares** where the dominant mangrove species is *A. germinans* followed by *R. mangle* and *Laguncularia racemosa*. Topographical and relative elevation data indicates that the main central section of this site is below sea level (-0.01 to -0.30m) and is surrounded by higher elevation ground (0.0 to 2.2m), where tidal flow is absent or limited throughout the area. As a result of the destructive hurricane forces causing structural damage to tree canopy (defoliation, fallen trees) in combination with stagnant water, the area has lost practically all its vegetation cover (See **Appendix A**, archive images and drone imagery). Both topographical and biological restoration are needed to return the mangrove forest to its original state (mix of basin and fringe forests). This objective could be accomplished by the combination of a targeted hydrological restoration and maintenance of existing well-delineated natural channels. This should be implemented in combination with the rehabilitation of existing man-made ditches and culverts, which are partially, or not functional at all, due to clogging by sediments of different composition (i.e., silt, sand) and both allochthonous and *in situ* wood debris transported by storm surges.

SAFE-Site and SAFE -Island. Sites A, B, C, and D area could be rehabilitated to pre-hurricane conditions by reforestation practices in areas where incipient or limited natural regeneration is occurring using a combination of low scale planting combining mangrove propagules, seedlings and saplings and different density under the safe-site (SAFE-S) methodology (**Figure 2A**). SAFE-S include the selection of sites where environmental conditions surrounding seeds/propagules/ saplings favor establishment and growth (Harper et al. 1961, Urbanka 1997).These sites represent conditions not only to facilitate recruitment, but also by a hierarchy of ecosystem specific hazards (e.g., hyper-salinity, disrupted hydroperiod) from which the safe site protect propagules/seedlings and developing plants (Urbanka 1997, Twilley et al. 1998, Rivera-Monroy et al. 2006b). The SAFE-S is a realized-niche space (e.g., Brokaw and Busing 2000, Chen et al. 2013) matching mangrove species eco-physiological tolerance and observed fertility gradients in the damaged/impacted area (**Figure A)**. This space can promote colonization where frequency and duration of inundation and porewater salinity are within ranges that do not represent stress conditions for plant growth and reproduction. Thus, hydroperiod needs to be restored first to warrant the functionality of the SAFE-I approach. For instance, the combination of this approach with dredging of natural channels increases the chances of optimal propagule establishment by acting as “migration corridors” delivering propagules produced in the SAFE-S into areas that are currently bare of vegetation. This condition either caused by tree mortality or natural disturbances, creates suitable habitat conditions for mangrove establishment. Further, to increase plant establishment and growth at larger spatial scales, SAFE -Islands (SAFE-I) will also be established (Urbanska 1997b, a). SAFE-I are patches characterized by high density and availability of various SAFE-S, and initially populated by species that were previously dominant in the impacted area. SAFE-I total area will vary depending on restoration site environmental conditions and surrounding landscape across elevation gradients and tidal creeks hydrological connectivity.

Site B: Site B is a 59.3-hectare mangrove forest located in the municipality of Aguirre as well, and with the boundaries of the State Park Bosque de Aguirre; this area has impacts similar in extension as observed in site A (**Figure B).** The mangrove wetlands in this area are mainly composed of *A. germinans* but also include areas where *Rhizophora mangle* and *Laguncularia racemosa* are present. Similar to site A, this site is below sea level (-0.0 to -0.45m) and also surrounded by higher elevation in the range from 0.0 to 0.60m; the lack of tidal flow is apparent as well. Forest structural and forest canopy is also evident along with changes in the topography as indicated by higher water residence time in the central areas of the site (**Figure B** and appendix A, archive images and drone imagery). Both water flow and biological restorations are needed to return and accelerate mangrove wetland natural regeneration. One key management strategy is to extend three (3) previously excavated channels dredged during the removal of derelict **vessels.** Fully opening these 3 channels will improved tidal water circulation and increas water exchange between the interior areas and the bay; this reestablished flow can promote natural mangrove forest regeneration and recovery close to channel l and provide a source of propagules needed to expand colonization of other unvegetated areas.

This area will be restored by using the SAFE-S and SAFE-I methodology (see description in Site A, p. 15) and the "modified compressed succession" (MC-S) (Kenworthy et al. 2018; Furman et al. 2018) technique widely used in seagrass restoration. We plan to adapt this technique to increase the probability of mangrove species establishment in areas characterized by extensive mangrove dieback with open spaces with occasional inundation by tides and seasonal precipitation. This restoration approach utilizes the most appropriate/suitable mangrove

species (i.e. ecophysiological adaptations) for the present environmental conditions. These include *Rhizophora mangle* (fringing locations) and *Laguncularia racemosa ((higher elevation; higher porewater salinities, long duration of inundation).* Depending on the current elevation impacted by the long-term lack of belowground biomass and erosion, topographical restoration will be implemented to reduce environmental stress. These localized site modifications will be followed by hydrological restoration to recuperate ecosystem services in the short term (e.g., above carbon storage) . For example, we will initiate restoration with the species *L. racemosa* , a shade intolerant plant, in areas with porewater salinities <50 ppt, and then induce replacement with species better adapted to higher salinity but shade tolerant such as *A. germinans*. We also plan to induce the expansion and growth rate of halophyte vegetation
(e.g. *Batis* sp, *Salicornia* sp.) to reduce soil temperature and light incidence thus increasing the probability of mangrove seedling survival in the MC-S units. This modified method uses readily available, seedlings and saplings to create planting pots ("Macetas" or planting units), in combination with natural organic matter or manure in areas where nutrient availability is low before hydrological connection. For instance, phosphorus is the primary limiting nutrient for seagrasses growing in calcium carbonate-based sediments and the addition of this nutrient stimulates faster growth of *S. filiforme* and *H. wrightii* (Short et al. 1985; Powell et al. 1989; Fourqurean et al. 1995). After sediment/soil nutrient analysis in the impacted areas in the JBNEER sites, we will add nutrients to accelerate growth and the reproductive stage in plants established in MC-S / "Macetas" units serving as functional propagule dispersion locations along rehabilitated tidal natural /man made channels.

Site C: Site C is a 103.6-hectare mangrove forest located in Quebrada de Melania also in the municipality of Aguirre, and within the boundaries of the Bosque de Aguirre. The forest is dominated by the mangrove species *A. germinans* followed by *R. mangle* and *L. racemosa*. The mangrove forest was heavily damaged by Hurricanes Irma and Maria. Both mangrove soil and sediments along channels were partially redistributed due to the lack of vegetation root system resulting in alterations of the local natural drainage and hydrology (**Figure C**) as observed in Sites A and B.

The main central section of the site is below sea level (approx. -0.0 to -0.22m) and is adjacent to higher elevations (approx. 0.0 to 0.60m) where tidal flow is apparent. Due to the destructive hurricane forces which caused structural damage to tree canopy, and the stagnant water, the forest has lost practically all its vegetation (See appendix A, archive images and drone imagery). Both topographical and biological restorations are needed to return the inundation/hydroperiod and reforestation of the mangrove forest. This can be accomplished by the rehabilitation and maintenance of existing release channels, ditches and culverts; some of these structures are not working at their maximum capacity because they are clogged and entrapped by solid, silt, sand, and wood debris due partially to hurricane impact.

This area will be restored using the SAFE-S and SAFE-I methodology (see description in Site A, p. 15 -16). and the "modified compressed succession" (Kenworthy et al. 2018; Furman et al. 2018) utilized in seagrass restoration as an adaptation to mangrove forest restoration.

Site D: Site D is a 17.5- hectares mangrove forest located within Jobos Bay (National Estuary Research Reserve) in the municipality of Quayama. This site is part of a mangrove research sentinel site (https://www.fws.gov/pacific/Climatechange/meetings/coastal/pdf). The site area is approximately 17.5- hectares; as in the other sites, the dominant species is *A. germinans* followed by R. *mangle* and *L. racemosa* species. The mangrove forest was heavily damaged by Hurricanes Irma and Maria, knocking down a number of trees (**Figure D**, see appendix A for images). This site has a smooth gradual elevation (approx. 1.0 to -0.42m) from the shoreline (North) to the most seaward direction (South) making the inundation and hydroperiod potentially optimal for the natural recovery of the forest, although direct hydroperiod measurements are recommended.

The level of wind and apparent storm surge in this site caused structural damage to the tree canopy, leaving behind a matrix of wood debris and standing dead tree trunks that are slowing down the natural drainage even when there is tidal exchange. In some areas, sediment has been lost; porewater salinity in these areas can reach mean values of 85 ppt. Vegetation cover is mostly absent (See appendix A, archive images and drone imagery). Despite this vegetation loss, it is apparent that no hydrological restoration is needed, although biological restoration is required. Also, ditches and culvert maintenance could accelerate recovery. Some of the culverts are not working at maximum capacity because they are clogged/entrapped by solid, silt, sand, and wood debris as result of hurricane impacts.

This area will be restored using the SAFE-S and SAFE-I methodology (see description in Site A, p. 14)

Forest structure transects

A survey of forest structure was performed along the transects where elevation was measured. Three years after Hurricane Maria's impact (Maria, 20 September 2017, category 4) and Irma passage to the north of Puerto Rico as category 5 (September 6, 2017) there is still evidence of defoliation and tree fall/mortality as a result of wind velocity (> 200 km/h). However, previous hurricanes may have contributed to changes in hydrology and hyper-salinity

(>60 ppt) conditions in some locations throughout the JBNEER. As a result of these pre-hurricane conditions, hurricane impacts exacerbated tree mortality by felling already dead standing trees, thus increasing the amount of dead wood on the ground. This increase in woody debris is currently impacting water residence time and circulation in low elevation areas in all study sites (A, B, C, D) (see Appendix Drone picture). For instance, live trees along transects in Site C were absent while density of woody debris was high with presence of patchy scrub mangroves dominated by *A. germinans* (see Appendix photos).

Overall, average tree height across all survey sites is low (< 8m) when compared to other mangrove forests growing in different environmental settings (> 20m ;e.g. deltas) (Simard et al. 2019) (**Figure 1a**). This coastal region is dry with apparent high evaporation rates that influence vegetation growth as indicated by the dominant dune vegetation/halophytes in higher elevations. One important climate variable controlling maximum tree height, not only in the case of mangrove trees but other species, is wind velocity, which can reach up to 16 miles per hour during the month of December, January, February and March at the peak of a dry season. Thus, the combination of high evaporation and wind fetch can contribute to saline and hypersaline soil porewater values in mangrove areas already impacted by hydrological changes as indicated by the dominance of the species *A. germinans* in sites A and D (**Figure 1a**). Indeed, the elevation survey shows that the dominant species of standing mangrove forest was the black mangrove (**Graph 1**); dead standing trees can measure up to 40 cm in diameter at breast height (DBH) also indicating the maximum potential growth under average climate and environmental conditions (**Graph 1**). These dead standing trees were already present before Hurricane Maria impact, and suggest the potential maximum growth/biomass mangrove forest can reach in these coastal regions under a predominantly dry climate across the JBNEER. For example, porewater salinity in these already hydrological impacted areas was on average 70 ppt (**Graph 2; Sites A, B, D)**. And although mangrove forests, as is the case of the black mangrove, can withstand high salinities (>50 ppt) on seasonal basis, persistent hypersalinity conditions trigger cumulatively extensive diebacks over several years (**Graph 2**) (Lopez-Portillo et al. 2005, Rivera-Monroy et al. 2006b, Mendez-Alonzo et al. 2008, Madrid et al. 2014, Medina et al. 2015).

In addition to salinity, surface water pH measurements were measured across transects in all sites (**Graph 3**). Values ranged from 6.5 (site A) to 8.7 (site B) indicating the wide variability in soil origin/composition and biogeochemical processes controlling organic matter decomposition and nutrient availability; this occurs in locations previously dominated by mangroves. In particular, acidic conditions are prevalent in Sites A and B (**Graph 3**). These values suggest a higher accumulation of organic compounds probable as a result of long-term accumulation of organic matter and wood debris. This pattern is in contrast with site D where pH values are also close to basic marine water values (pH, 8.1), even when the site lacks tidal exchange. Further studies are needed to elucidate the seasonal net differences in soil and overlying water pH values, which fluctuate along with daily and seasonal hydroperiod.

VIII. TIDAL EXCHANGE

As a result of Hurricane Maria and Irma's negative impacts there were significant changes in mangrove forest structure through defoliation, tree snapping, and uprooting. It is apparent that these impacts on previously stressed vegetation (different levels of tree mortality) will determine the degree and extension of natural regeneration (e.g., species composition), vegetation successional patterns, nutrient cycling, and the potential permanent loss in soil elevation at all 4 sites (**Figures A, B, C and D**). During this field survey, it was apparent that the system has been chronically impacted by major hydrological/hydroperiod alterations and becoming a major impediment in the natural regeneration of mangrove wetlands; the limited regeneration and hydrological connection in most of the areas have already triggered major mangrove area loss over several decades. The impact of Hurricanes Maria and Irma further exacerbated this condition. However, in some locations the preexisting hurricane tidal exchange and flow indicate that all 4 Sites had a favorable elevation gradient from land to the shoreline where hydroperiod (flooding duration frequency of inundation) might be adequate to promote natural regeneration and tree growth. Thus, the partial rehabilitation of previous existent structures (ie.. culverts) and channels with some target planting using the SAFE-S approach (see above) can act in synergy to rehabilitate some of the most damaged areas before and after hurricane impact (**Figure 3**). Below is a brief description of the hydrological patterns topographic features in each site.

Site A had four main pre-hurricane tidal flow discharge points. The main discharge point is located to the North via a natural creek that discharges into Jobos Bay proper but it now has restricted flow due to the impacts of Hurricanes Irma and Maria. The other 3 discharge points were channelized by a series of culverts and man-made ditches to accommodate for the construction of the PR 7710 road, which divides Site A from Site C. In the past, these discharge points directly discharged into Quebrada Melania mangrove forest and into the Quebrada Melania creek; tidal exchange in this locality is absent with no observed flow during the field survey (**Figure 3A**).

Site B had two main tidal flow discharge /exchange points. One to the East that drains into the Quebrada Melania creek, but with restricted flow, and one to the West, which used to discharge directly to Jobos Bay (**Figure 3B**).

Site C had 3 mayor tidal flow discharge points. One to the West that directs water flow into various points along the Quebrada Melania creek. The other two are culvers at this site; one connecting to Site A in the Northern region that is no longer active while the second in the South direction used to discharge into the Laguna de Pozuelo (**Figure 3C**).

Site D has two culverts that are no longer working to the North that drained water from u higher elevations, particularly precipitation into the system. The topographic relief has a natural gradient from land to the seashore that provides a natural and functional relative elevation for tidal flow and exchange. However, surface water flow is completely restricted in some areas due to accumulation of debris and fallen trees caused by the hurricanes (**Figure 3D**).

The precarious hydrological conditions in all sites negatively impacting mangrove natural regeneration as a result of the cumulative negative pre- and post- hurricane impacts need to be addressed using direct interventions to promote the natural regeneration of mangrove wetlands in the JBBB. One of the pressing tasks is to start a wetland rehabilitation program by implementing hydrological restoration of natural creeks and man-made structures, which were already non-functional previous to the impacts of the hurricanes. This condition is partially the result of the economical inability of the state and local government to restore and maintain the natural and man-made discharge points in optimal conditions for mangrove conservation and sustainability.

IX. MAGROVE RESTORATION METHODS

Successful mangrove forest restoration requires careful analysis of a number of factors in advance of attempting actual restoration (Twilley and Rivera-Monroy 2005). First, for a given area of mangroves either present or removed , the existing watershed/relative elevation needs to be defined including changes to the coastal plain hydrology/hydroperiod that may have impacted the mangrove habitat (Lopez-Portillo et al. 2017).

Second, careful site selection must take place, including the history of the site in terms of natural regeneration, forest structure, and relative elevation. Third, clearly stated goals and achievable and measurable success criteria needs to be defined and incorporated into a proposed monitoring program. Fourth, the restoration methodology must also reflect an acknowledgement of the history of routine failure in attempts at mangrove restoration and proposed use of proven successful techniques (Lewis 2000, Bosire et al. 2008). Finally, after the initial restoration activities are complete, a monitoring program must be initiated and used to determine if the project is achieving interim measurable success to indicate whether any mid-course corrections are needed (Twilley et al. 1998, Lewis and Gilmore 2007). This long-term monitoring is a critical step that is usually lacking in most wetland restoration projects.

Mangrove wetland restoration is only a solution if protection of the remaining mangrove habitat is initiated, and before too much critical area is lost as is usually the case when major hydrological alterations and impacts are ignored. The steps described above include requirements of appropriate and successful on-site mangrove forest restoration. It is important to work together with communities, organizations and local government agencies such as the DRNA and NOAA to advance restoration and rehabilitation objectives in the long term. A successful program must reach beyond planting seedlings and consider natural water flow and salinity regime to increase the success rate for restoring large areas of degraded mangrove forest (Twilley et al. 1998, Rivera-Monroy et al. 2006a, Rivera-Monroy et al. 2011, Rivera-Monroy et al. 2013).

Some of the most common steps for mangrove restoration and rehabilitation are (Field 1998, Lopez-Portillo et al. 2017):

1. Recognize and investigate the community ecology and structure of the naturally occurring mangrove species at the site, especially species reproduction patterns, spatial distribution, and natural/induced successful seedling establishment,
2. Identify the normal hydrologic patterns that control the distribution and successful establishment and growth of targeted mangrove species,
3. Assess the modifications of the mangrove environment that occurred and that currently prevent natural secondary succession,
4. Only utilize actual planting of seedlings as an integral part of the rehabilitation program after it is concluded that natural recruitment will not provide the quantity of necessary plant densities and growth rates observed in control sites (i.e., no-impacted) as explicitly stated as performance measures to achieve project success.

A. General Restoration Approach

Mangrove wetland restoration is challenging, particularly when both below and above biomass has been altered/removed. Our general approach is to restore mangrove wetlands in the Park by restoring hydrological/patterns water flow to promote rapid colonization and advance the successional stages of native plants. Natural occurring plant succession takes many years to occur and without our restoration intervention to expedite this key secondary succession, these mangrove injuries covering large extensions may hardly recuperate or may even cause stress to the adjacent healthy forest; this process might include the eventual fractionation or total loss of the habitat unless hydrological patterns/hydroperiod are reestablished.

B. Specific Restoration Techniques

Hydrological/hydroperiod restoration

Hurricanes Irma and Marias' destructive forces caused substantial structural damage to tree canopy, leaving behind a matrix of wood debris and standing dead tree trunks that in some cases impede natural drainage during tidal inundation, particularly along creeks and man-made structures. In some areas, sediment resuspension and erosion has enclosed extensive areas promoting the entrapment of rain and tidal water; in the case of marine water long term residence in combination with high evaporation has increased soil and porewater salinity. Additionally, continuing erosion and partial sediment transport have negatively affected natural drainage network promoting high sediment accumulation in man-made canals, tidal channels, ditches and culverts that result in the absence of water exchange (tidal, precipitation) between the wetland area and the adjacent estuarine waters.

In order to restore the hydroperiod/water flow to the system, the maintenance of ditches, culverts and the channel maintenance dredging must be implemented in order to regain at least minimum flooding frequency/duration and net water exchange between deteriorating wetlands and adjacent estuarine waters; this includes freshwater discharge from points of entrance in the northern region of the JBNEER.

Recommended Actions

Site A. Two culverts and one ditch (700 meters long) along the South side of State Road PR7710 need to be cleaned out of debris, sediment deposit and vegetation overgrowth in sections where water flow is impeded. One man-made drainage channel requires the removal of debris, vegetation over growth and re-excavation (maintenance dredging) to allow tidal water flow to return to the southern section. An excavator is also needed to dredge an area of approximately 100 meters long by 2m wide and up to a meter deep representing a total volume of $200m^3$.

Also, the North creek requires cleaning of debris and re-opening to maximize water flow into the northern side of system (**Figure 4A**).

Site B. During vessel salvage operations, post Hurricane Irma and Marias' impact, three major channels were partially opened to extract several vessels that had washed up on top of the mangrove forest canopy. We propose to take advantage of these channels and extend them towards the damaged areas to promote water flow and enhance tidal exchange and water flow. A floating excavator can dredge an area of approximately 70 meters long by 2m wide and up to a meter deep; this is approximately 140 m^3 of dredge material along channel 1 and 2. In the case of channel 3 this rehabilitation action requires a dredged area of approximately 90 meters long by 2m wide up to a meter deep (180 m^3 ; **Figure 4B**).

Site C. Debris removal is needed in one culvert at the most southern area and one ditch (700 meters long) along the South side of State Road PR7710; removal of sediment deposits and mangrove tree overgrowth in the middle of the channels is also needed. Similarly, two man-made drainage channels require debris removal and re-excavation (maintenance dredging) to reestablish water flow /exchange with the Quebrada Melania creek. A floating excavator needs to dredge an area of approximately 50 meters long by 2m wide and up to a meter deep (total volume of $100m^3$) to maximize water flow into the southern side of impacted area (**Figure 4C**).

Site D. Two culverts at the most northern section of the site require extensive debris removal of sediment deposit and mangrove tree overgrowth occurring on top sediment deposits that impede water flow. Due to the topographic relief and current hydrological connectivity, we do not anticipate dredging maintenance in the long term in this site (**Figure 4D**).

Mangrove Ecological Restoration.

We strongly recommend the implementation of community-based ecological mangrove restoration approaches (Bose et al 201X, Lopez-Portillo et al 2017) throughout the involvement of local stakeholders, universities, fisherman and both profit and non-for-profit organizations. These collaborations can warrant a sustainable future of mangrove restoration projects at different temporal-spatial scale in the JBNEER. Given the monetary and human capital investment needed for the implementation and success of restoration and rehabilitation projects, it is paramount to consider all different potential strategies to maintain restoration activities in the long term. Particularly when dredging/culvert maintenance is required in areas with major human impacts. This community-based approach needs to be accomplished by including science-based data and information to support actionable science to rehabilitate mangrove ecosystem services, already identified by JBNEER management strategic program. The current mangrove status regarding deforestation and hydrological alterations caused by Hurricanes Maria and Irma represent an opportunity to reassess the best way to optimize mangrove conservation efforts within the park boundaries. Also of critical importance, is to link restoration objectives with the JBNEER management plans to acquire/secure funding to make both restoration and conservation initiatives sustainable, especially the long-term funding of hydrological restoration. And moreover, in the context of climate change, since it is expected that landscape level disturbances, like tropical storms, will increase in strength and frequency. The question is not if another hurricane will impact the park, but when and where and planning to mitigate future impacts have to be considered in any mangrove wetland conservation/management plan including restoration/rehabilitation initiatives. Although, currently there is not a detailed, explicit economic valuation of mangrove ecosystem services in the JBNEER, it is expected, based on other mangrove ecosystem assessments, that the value might be at least 150 million dollars, for instance , just in the case of mangrove wetland carbon storage (e.g., Jerath et al. 2016).

Mangrove stock collection.

Due to the low density and limited extension of healthy mature mangrove forest stands in the JBNEER in combination with damaged mangrove areas in each site previously described, it is expected that the natural recruitment *per se* will not provide, in the short term, the necessary seedling and sapling densities to eventually match currently observed growth rates and stand densities in no-impacted sites (i.e. "control sites"). To eventually restore impacted areas to pre-hurricane conditions it is critical to use a combination of hydrological alterations and targeted planting strategies to promote regeneration at large spatial scales. The concept here is to induce/initiate a successional stage by combining propagules, seedlings and saplings utilizing the SAFE-SITE (SAFE-S) and SAFE-ISLAND (SAFE-I) (see section VII) approach under site-specific criteria regarding species composition and forest structure (tree height, density). Because hydrological connectivity is a major venue for propagule dispersion, it is expected that once this connectivity, maximized by the SAFESITE approach, will accelerate natural regeneration in areas where a combination of high fertility, low soil stressors presence (salinity, hydrogen sulfide), and adequate hydroperiod (frequency, duration, depth) will promote plant growth. However, the first step should be the rehabilitation of the hydrodynamic/hydroperiod regime to maximize restoration efforts, including monetary investment, by promoting propagule dispersion, increased plant survival rates and plant growth. Thus, the first phase is hydrological rehabilitation followed by the deployment of SAFE-SITES across areas with a defined combination of specific hydroperiod, stressors (e.g., hypersalinity), and resources (soil nutrient concentrations) values (species specific) to promote/enhance plant establishment and development.

Mangrove seedlings and saplings will be collected from four pre-selected donor sites by manual harvest, coring plants using a combination of direct removal via hand, shovel or using an iron corer with a diameter of about 10-15 cm depending on the age class (i.e., combination of diameter and height) of the selected individuals. The corer is inserted into the ground for about 20cm to 25cm. Coring will be performed to minimize damage to the roots of the target seedlings to be collected. A total of 300 SAFE-Sites (i.e., cluster of plants that have the potential for maturity and seed production and propagule dispersal, see appendix A image 2) containing 5 – 10 seedlings and /or saplings will be transplanted at the restoration sites. The number of plants per dispersal centers will fluctuate depending on the plant size and species and site conditions (combination of hydroperiod, stressors, resources). At **Site A**, 50 SAFE-Sites will be installed containing approximately 500 plants. **Site B**, will host 100 dispersal SAFE-Sites for a total of approximately 1000 plants; while at **Site C,** 150 safe sites will be deployed (1500 plants). SAFE-Sites will be nestled within SAFE-Islands across optimal sites defined after the hydrological rehabilitation and hydroperiod. Given the current elevation gradient and hydrological connectivity observed in **Site D,** no SAFE-S/SAFE-I will be installed in this location. The spatial arrangement of the SAFE-S and SAFE-I within each location will be based on a repeated measurement random block experimental design (**Figures 5A, 5B, 5C**).

Nursery location.

Additionally, we are proposing to establish a mangrove nursery area within the property of Jobos Bay National Estuary Research Reserve (JBNERR) to accommodate the restoration stock material. Plant stock material will be collected within a year prior to the restoration start date to allow time for the plants to adapt to in situ conditions and reproductive state to serve as viable units for the SAFE-Sites (**See appendix A, image 2**).

Transport of mangrove propagules, seedlings and saplings.

Mangrove propagules will be collected from control /undisturbed forest stands adjecent to the impacted area and during the production season. They will be placed directly into the collection crates and will be transported to the temporary intertidal holding area. Transportation will take place during the morning or under mild weather condition to avoid overheating and water loss. Double-layered fine mesh nets will be used to cover fresly collected seedlings/saplings from direct sunlight during transportation .

Potting/Replanting of Mangrove propagules.

Collected mangrove seedlings/saplings will be checked for any root damage and cleaned before replanting. The propagules will be inserted individually into a polyethylene garden pot pre-filled with a right amount of in situ sediment to protect plant roots and under similar pore water salinity conditions of sites to be restored.

Establishment of mangrove seedling's holding area.

Temporary holding areas will be established outside the restoration areas to store the collected seedlings prior to transport and to minimize relocation stress. The proximity or the location of the temporary holding area is critical for logistic reasons. Similar environmental conditions at the collection site and the holding areas promote quicker recovery (e.g., leave loss/roots) of the collected seedlings maximizing survival rates.

Monitoring methods.

Mangrove Plants. Given the importance of promoting seedling and sampling growth, we will measure plant height (H) and basal diameter (BD), preferably after one week of planting to establish a baseline to monitor survival and growth rates. If plant survives the different stages from transfer to replanting, the measurements will be repeated at 3-week intervals; in addition to the measurement of H and BD, the number of leaves will be counted to establish a relationship with plant survival rates. In case of plant mortality, the plant will be replaced, hence the importance of assessing plant status after 7-10 days of planting. A subsample of plants within the plant dimensions will be dried to determine the initial biomass to estimate productivity and eventual assessment of carbon storage at different levels of forest development. All plants will be tagged (zip ties with aluminum tags) to keep data records and determine individual plant development. A map showing plant spatial distribution will be produced to evaluate the impact of local environmental conditions (i.e., hydroperiod, stressors, fertility variables) across the target planted area and determine potential and realized natural recruitment.

Soil. Previous to planting, soil samples will be taken to measure organic matter content (%), bulk density, total carbon, organic carbon, total nitrogen and total phosphorus concentrations. Soil texture will also be evaluated at each planting site. After planting, soil pore water salinity (at 20 cm) will be monitored using standard methods at the same time H and BA are measured. Salinity will be measured using a refractometer. Temperature in the soil (~20 cm depth) and air will be recorded every hour using HOBO sensors deployed at 1-2-month periods. Inorganic nutrients (NH_4, NO_3 + NO_2, PO_4) in pore water at the planting site will be measured at the beginning of the planting and at least every 6 months and for the duration of the project. At least two (replicate) air HOBO temperature sensors will be placed above the maximum high-water level to monitor air temperature in each restoration site (A, B, C, D)

Water. We will deploy three water level recorders (sonic) in three sites to monitor frequency and duration of inundation and water level every hour. Data will be retrieved monthly. One temperature HOBO sensor will be deployed at each site and placed in the water column, 10 cm from the sediment; data will be registered every hour.

Immediately prior to initiate restoration activities, forest structure (time zero) and productivity will be conducted in mangrove stand close/adjacent to the restoration areas. this information will be used to evaluate/define restoration goals, including forest density, basal area distribution, and maximum tree height. We expect to start the project in 2022 and to be completed by September 2025.

X. SUMMARY and CONCLUSIONS

Accelerating and enhancing the natural recovery of mangrove wetlands will offset observed net mangrove area loss as result of the combined impact of hurricanes in 2017 and past cumulative-long term negative impacts (e.g., hydrological alterations associated land use/change) within and around the JBNERR. Thus, a comprehensive assessment and evaluation of the extension of the current damage will help to ameliorate, for example, potential carbon emissions and rehabilitate and improve natural wetland regeneration and natural resilience in this coastal region. Hydrological restoration to induce natural regeneration of mangrove wetlands is recommended in areas impacted by hurricanes Maria and Irma. Rehabilitation/restoration efforts are needed to return the inundation/hydroperiod and in synchrony with reforestation practices. This would be accomplished by the maintenance of existing release channels, ditches and culverts that are not working at their maximum capacity because they are clogged, entrapped by solid, silt, sand, and wood debris due to the hurricanes.

This assessment focused on a specific set of four candidate sites (A, B, C, D) in Jobos Bay and at the adjacent park Parque de Aguirre that were identified in a comparison of pre- and post-storm imagery. Four sites were assessed for mangrove species composition, water depth, tide stage, wave exposure, general current spatial patterns, salinity, pH., temperature, relative elevation, mangrove physiognomy, qualitative sediment composition, and damage/injury type. Sites A, B, C, and D could be rehabilitated in the long term to pre-hurricane conditions by reforestation practices in areas where incipient or limited natural regeneration is occurring using a combination of low scale planting of mix mangrove propagules, seedlings and saplings with different density using the safe-site (SAFE-S) methodology. Hydroperiod needs to be restored first to warrant the functionality of the SAFE-I approach. The central areas of the three proposed sites (A, B and C) are below sea level (approx. -0.0 to -0.40m) with adjacent higher elevations approx. 0.0 to 2.0m) where tidal exchange is currently limited.

By implementing the aforementioned restoration techniques and maintenance, the mangrove forests will gradually to its be restored to its original state thus returning the ecological services needed in the area.

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Figure 1. Aerial image of Jobs Bay, Puerto Rico.

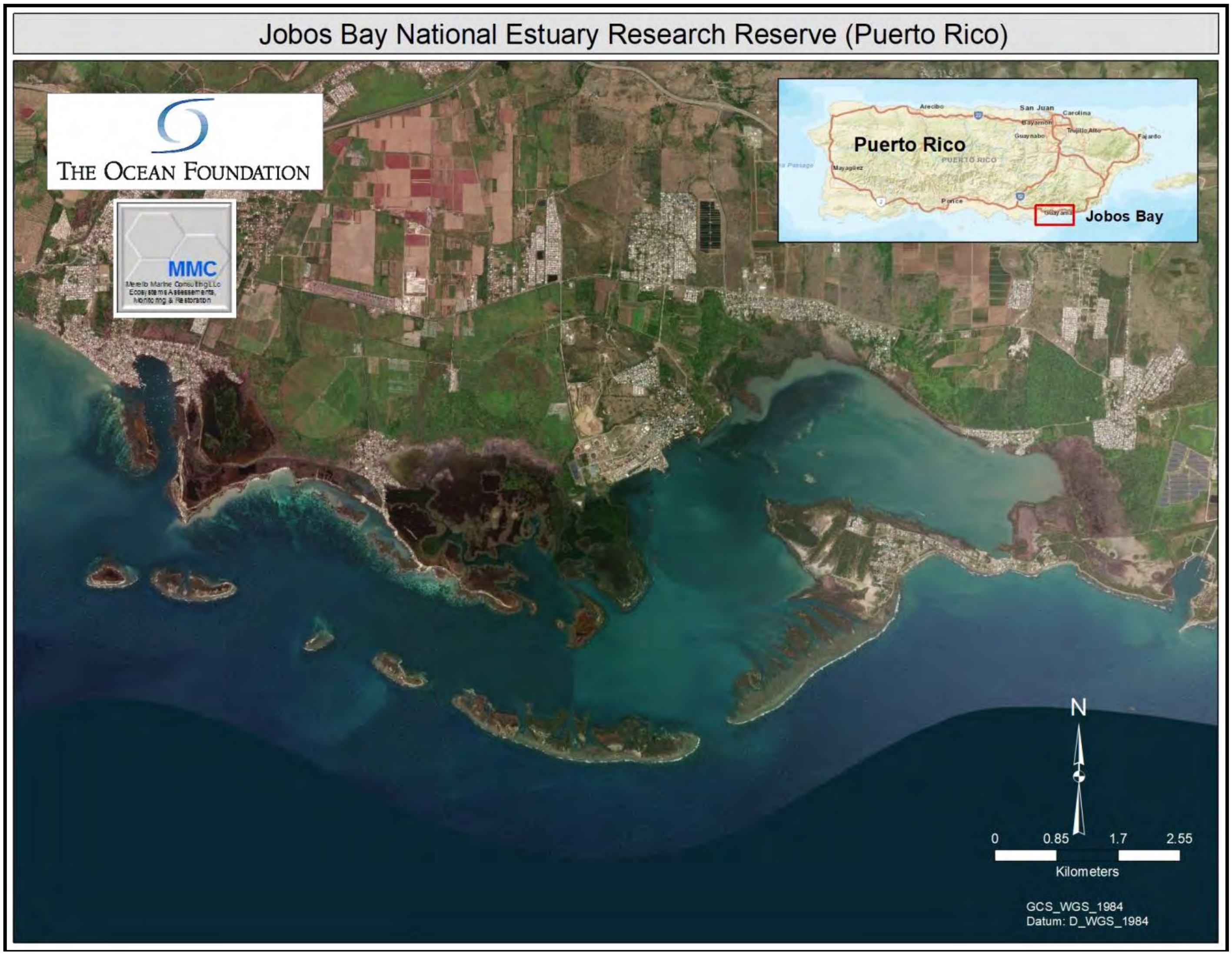


Figure 2. Aerial image of Jobos Bay, Puerto Rico showing the mangrove study sites (Site A, B, C, and D) selected by JBNERR/DRNA, the Ocean Foundation and Merello Marine Consulting for the Mangrove Feasibility Study for the restoration activities.

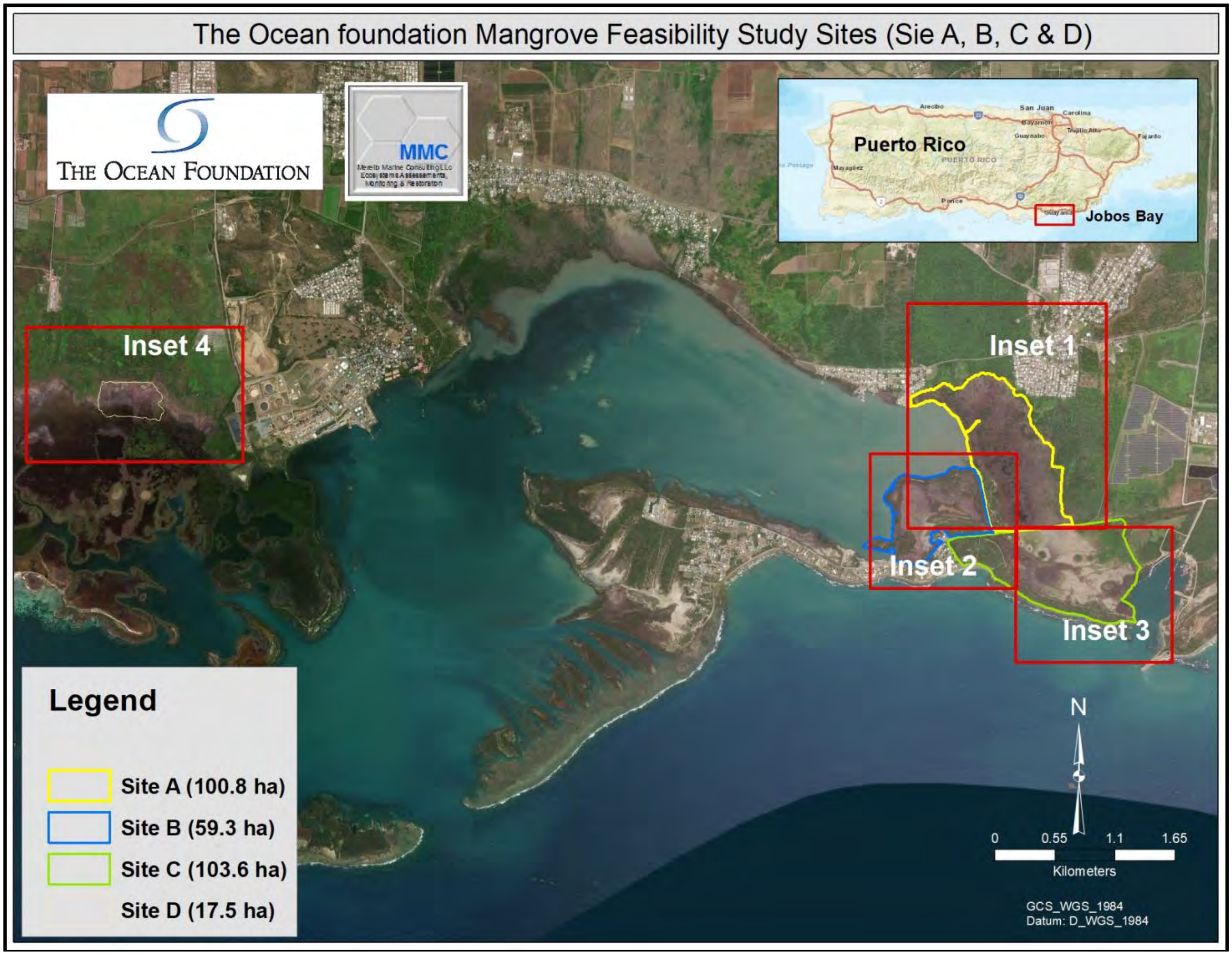


Figure A. Aerial image of Site A showing the feasibility study area topography (Inset 1).

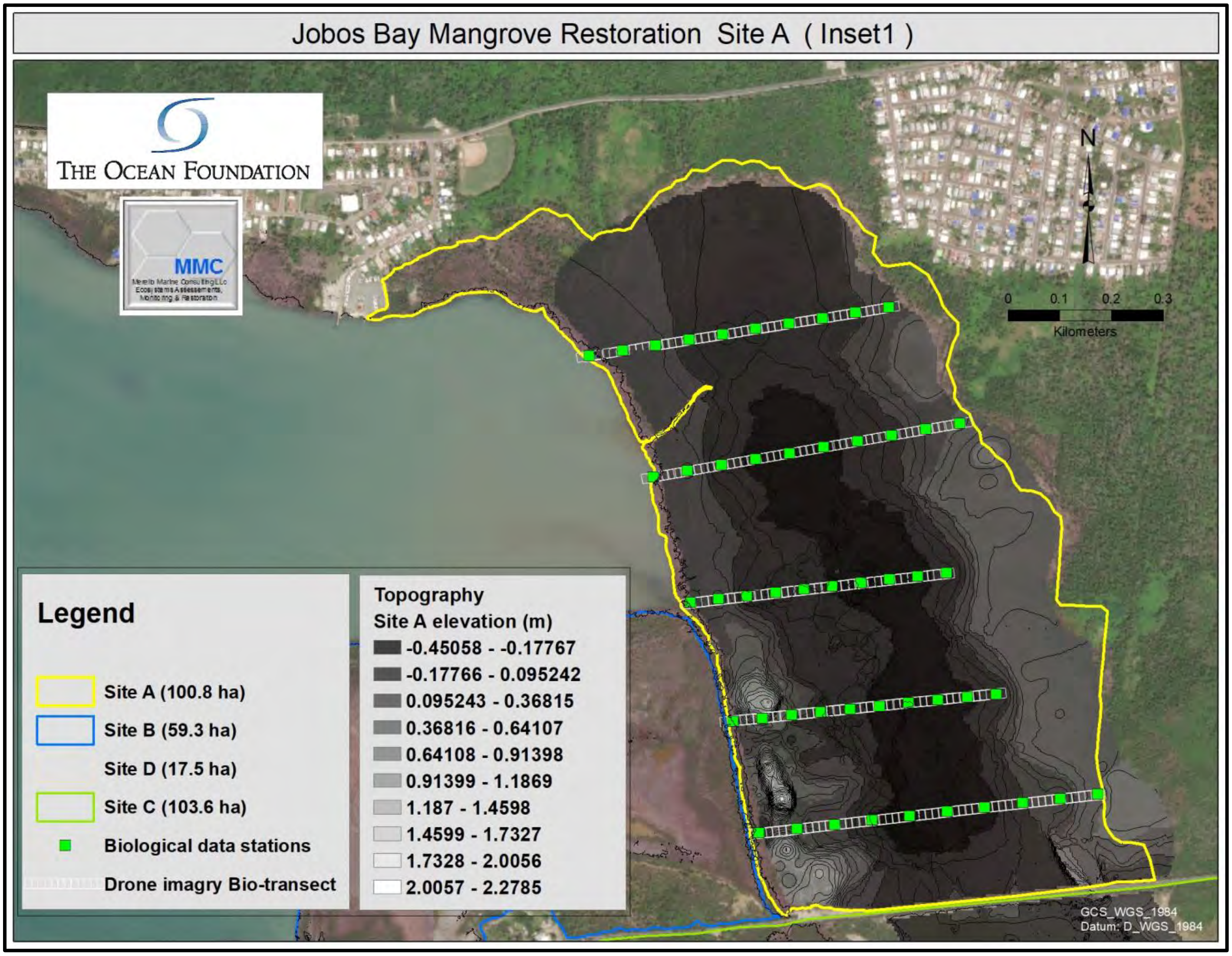
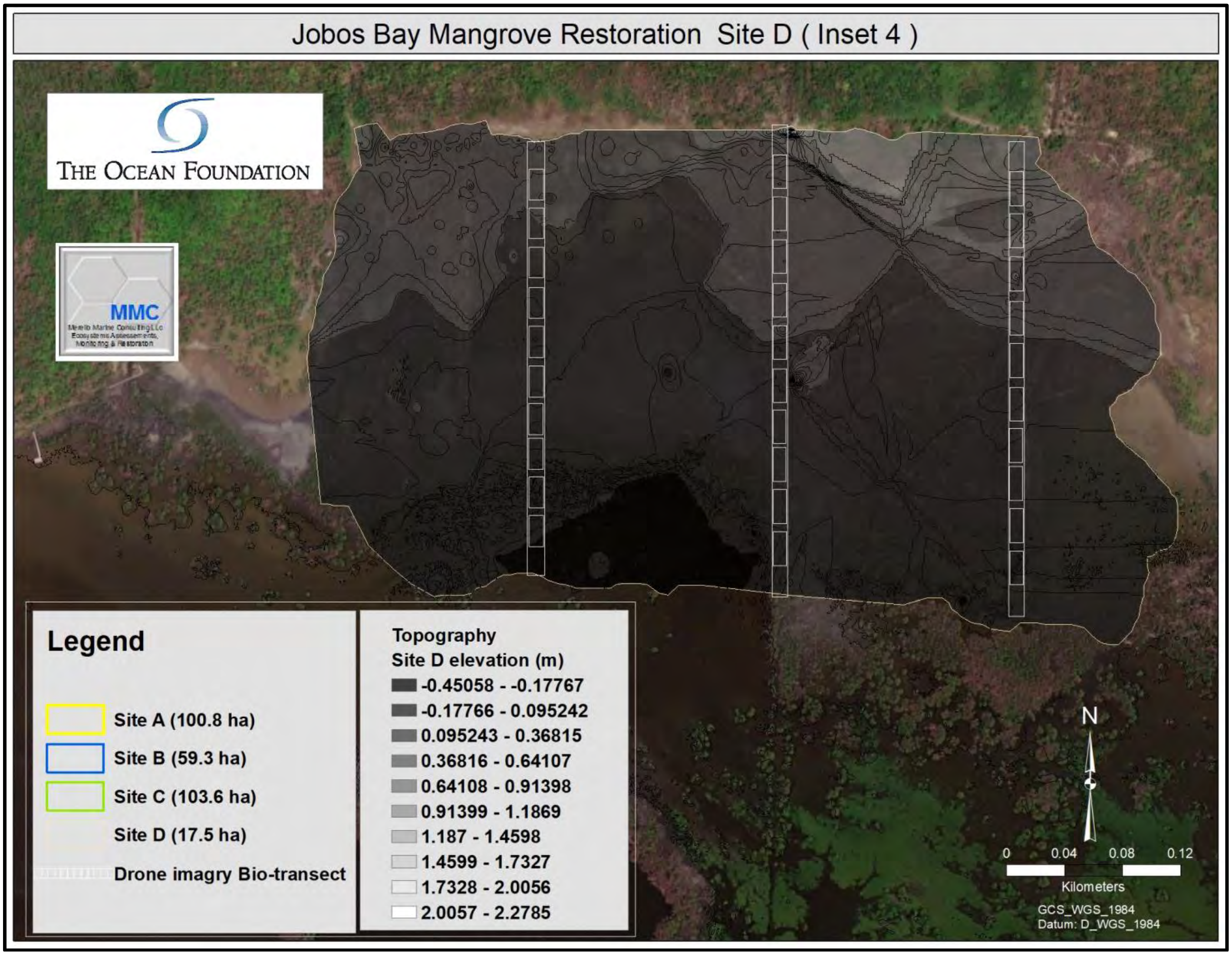


Figure 2A. Sites with different mangrove seedlings/saplings/propagule density showing different stages of colonization. Vegetation density represents different stages in the SAFE-SITE (Safe-S) and SAFE-ISLAND (Safe-I) conceptual framework. Safe-S includes the selection of sites where environmental conditions surrounding seeds/propagules/ saplings favor natural regeneration establishment and growth (Harper et al 1961; Urbanska 1997) and based on species ecophysiological adaptations. SAFE-S requires hydrological rehabilitation as a first step in restoring/rehabilitating negatively impacted/injured mangrove wetlands. See text for explanation.

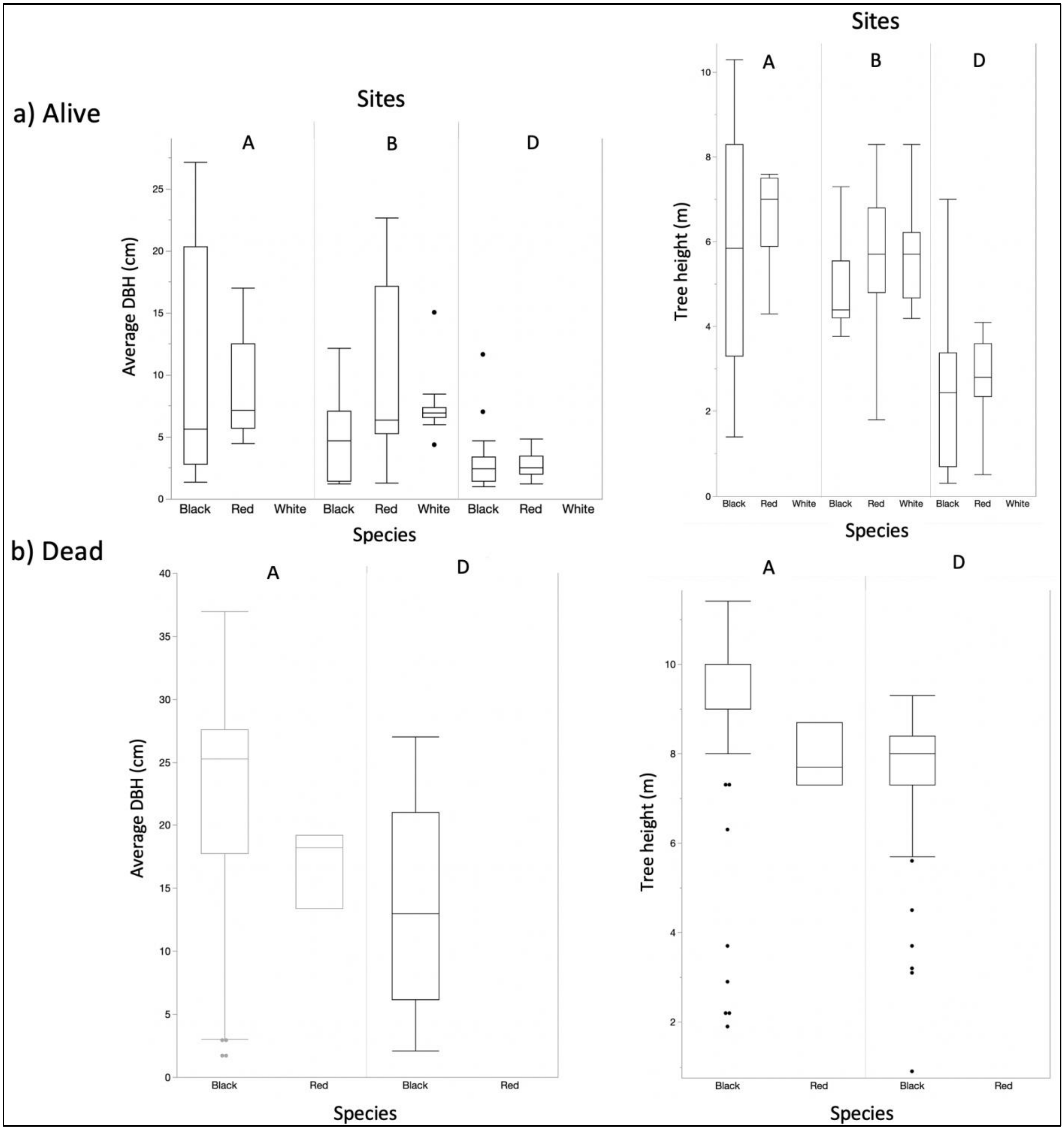
Figure B. Aerial image of Site B showing the feasibility study area topography (Inset 2).

Figure C. Aerial image of Site C showing the feasibility study area topography (Inset 3).

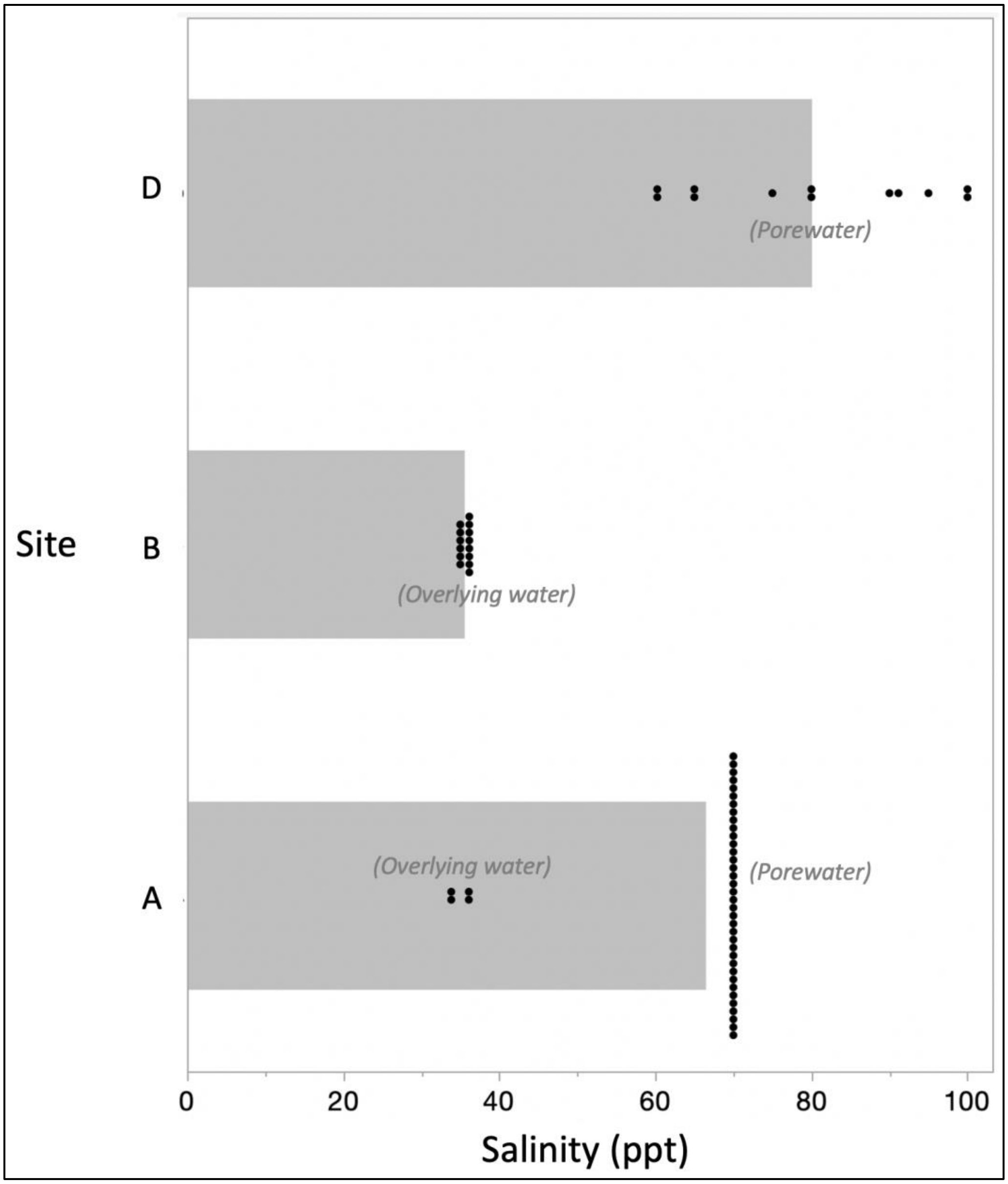
Figure D. Aerial image of Site D showing the feasibility study area topography (Inset 4).



Graph 1. Diameter at breast high (DBH) and tree height along transect per survey site. A) Alive trees. B. Dead trees.



Graph 2. Surface water salinity and soil porewater salinity along transects in survey areas in the JBNEER. See Figure for site and transect locations. Surveys were performed on August 20, 2020.



Graph 3. pH values in soil porewater along transects in survey areas in the JBNEER. See Figure for site and transect locations. Surveys were performed on August 20, 2020.

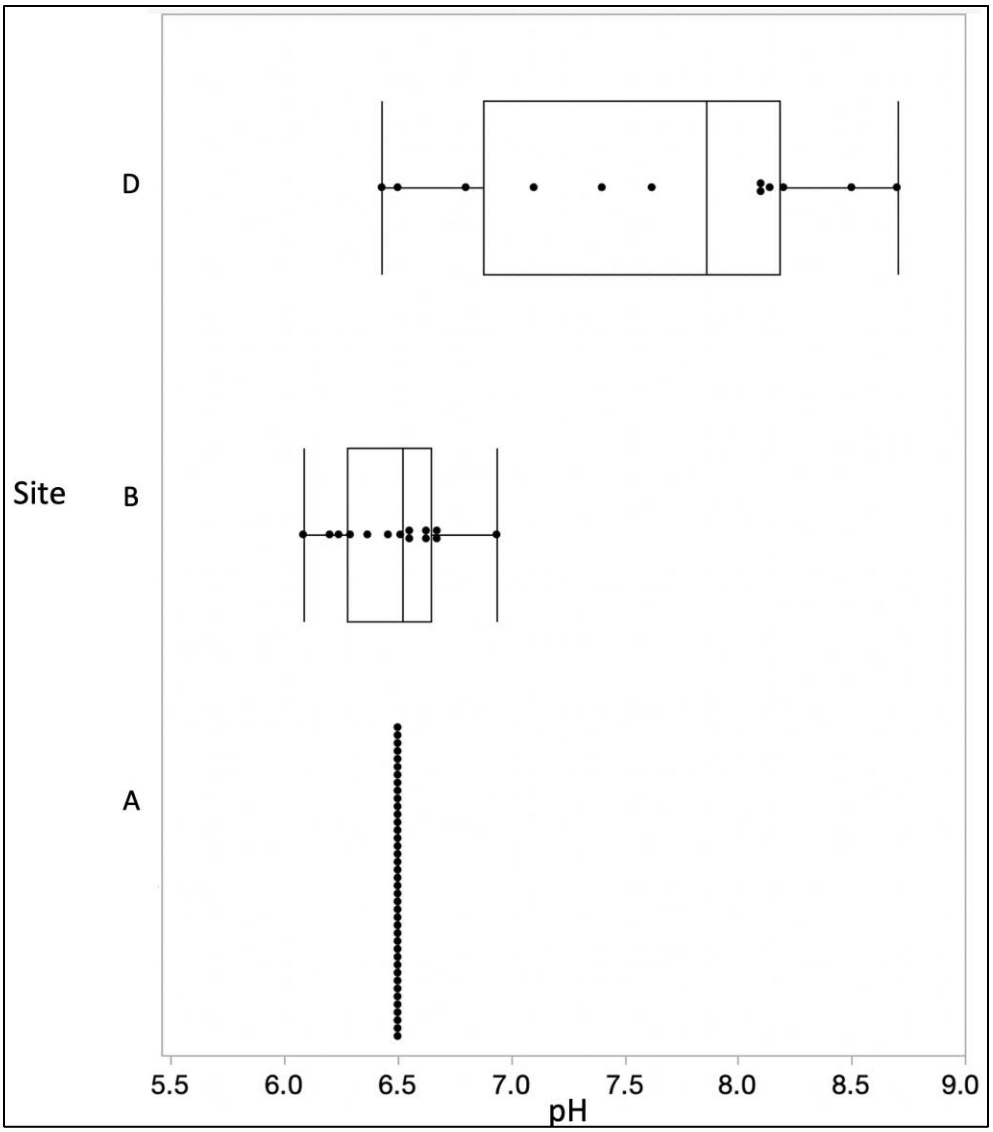


Figure 3. Pre-hurricane water flow at Sites A, B, C, and D.

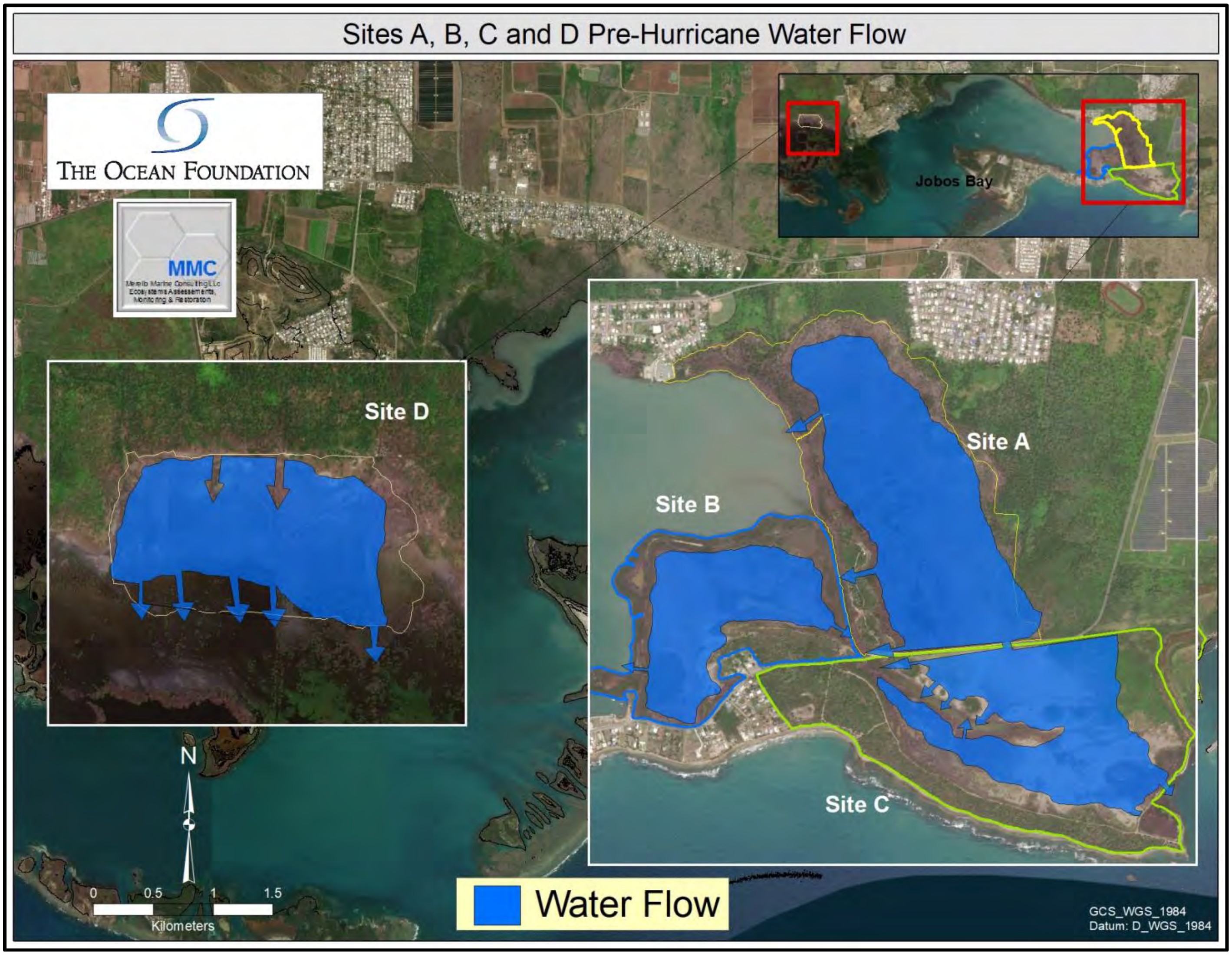


Figure 3A. Site A general water flow.

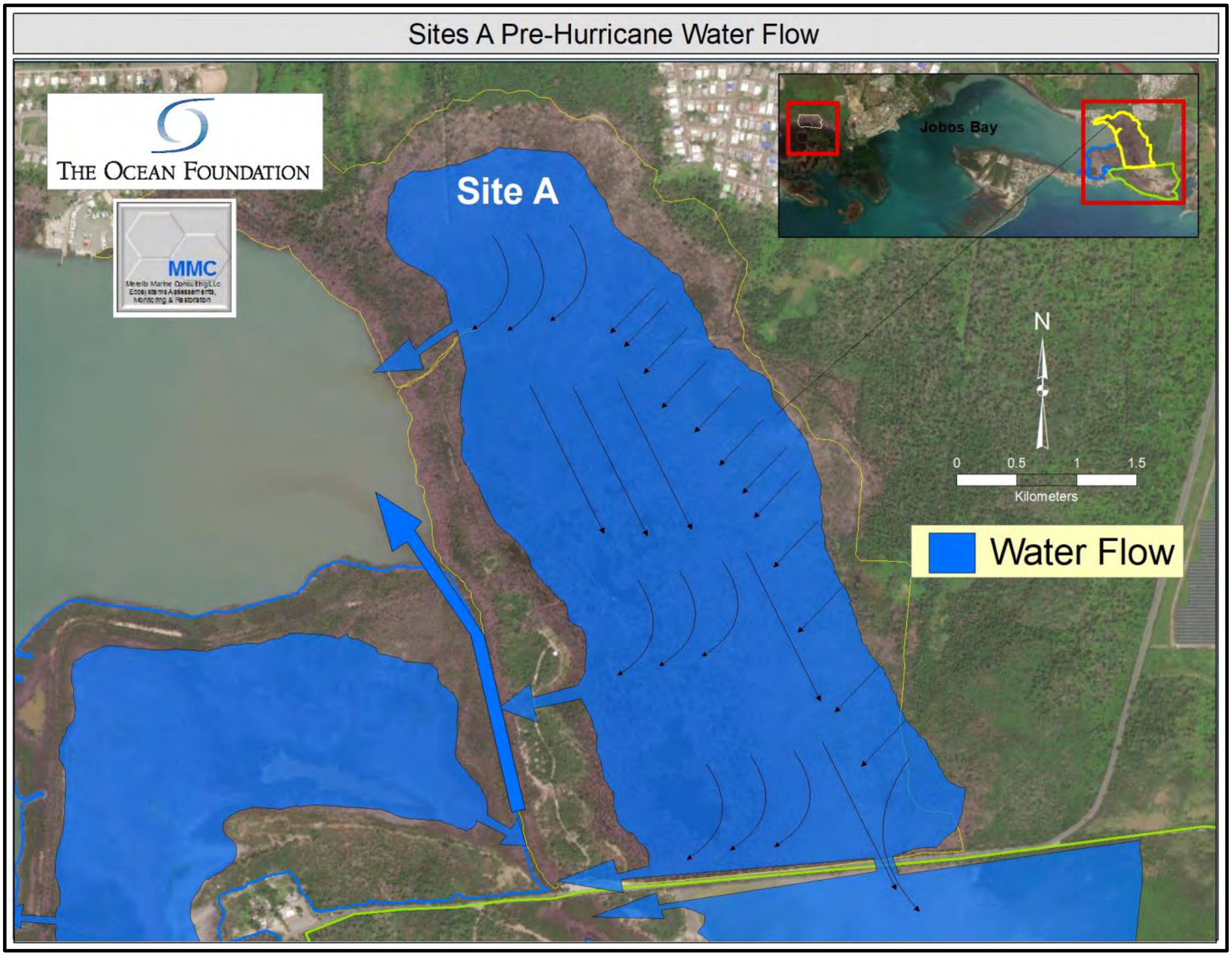


Figure 3B. Site B general water flow.

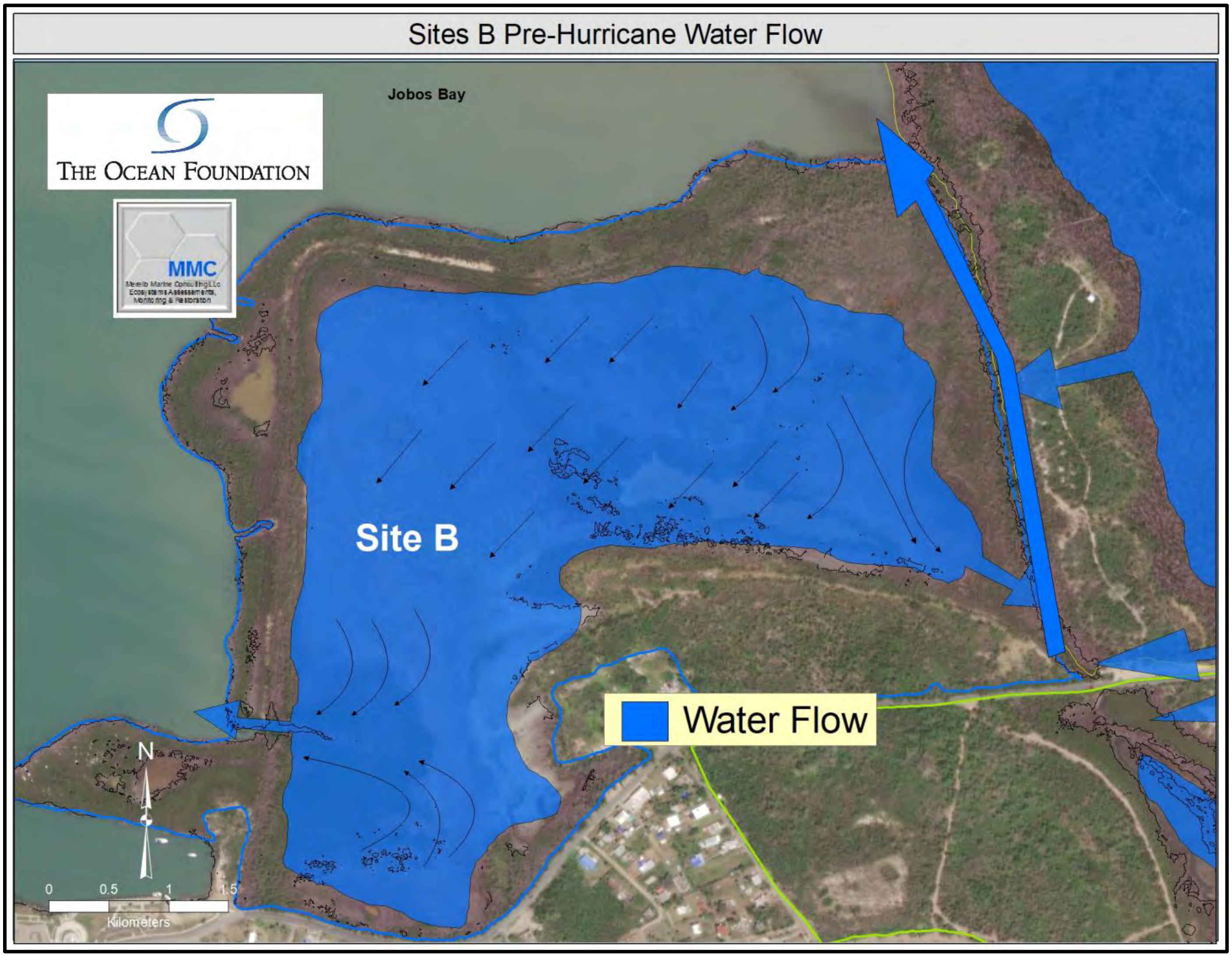


Figure 3C. Site C general water flow.

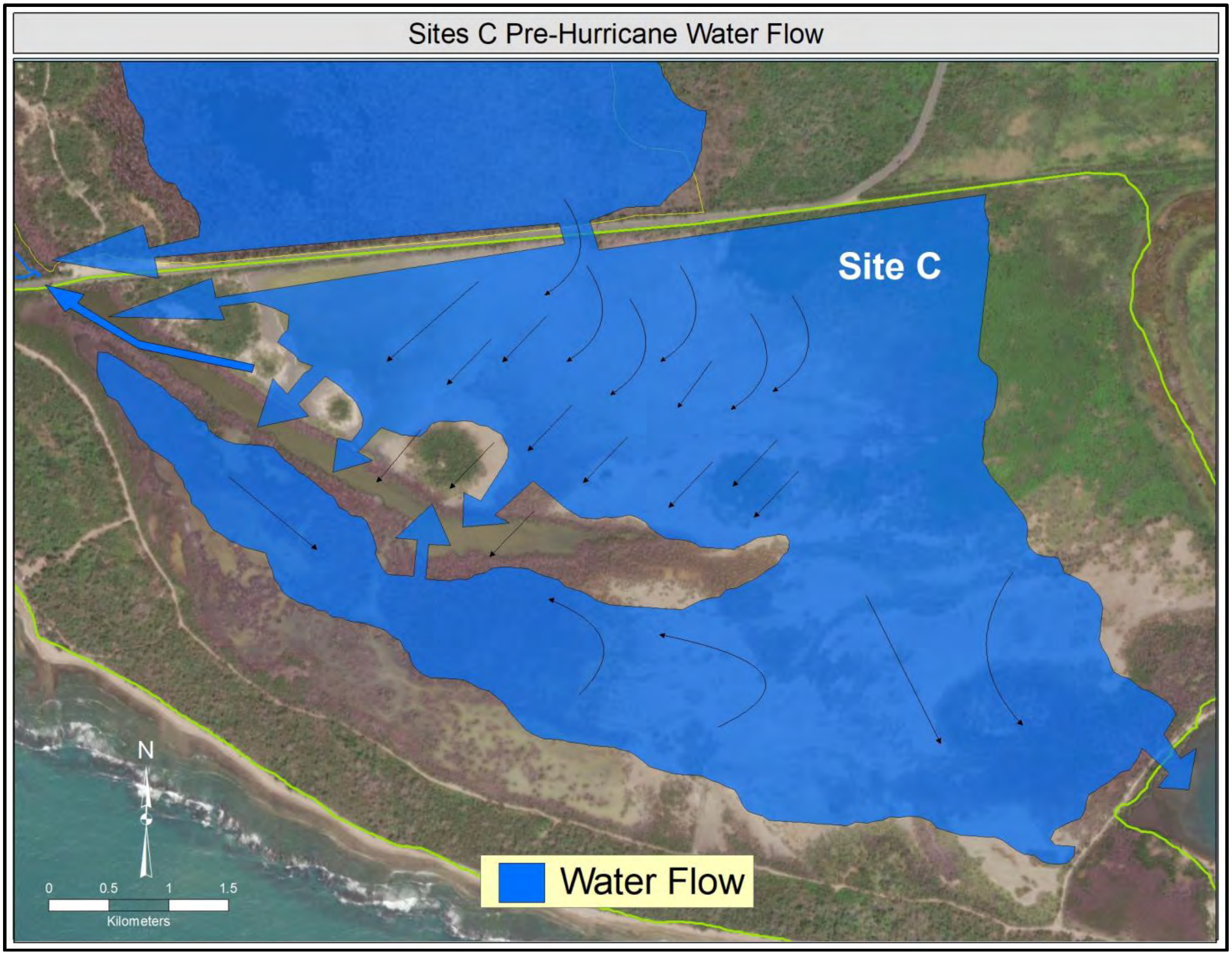


Figure 3D. Site D water flow.

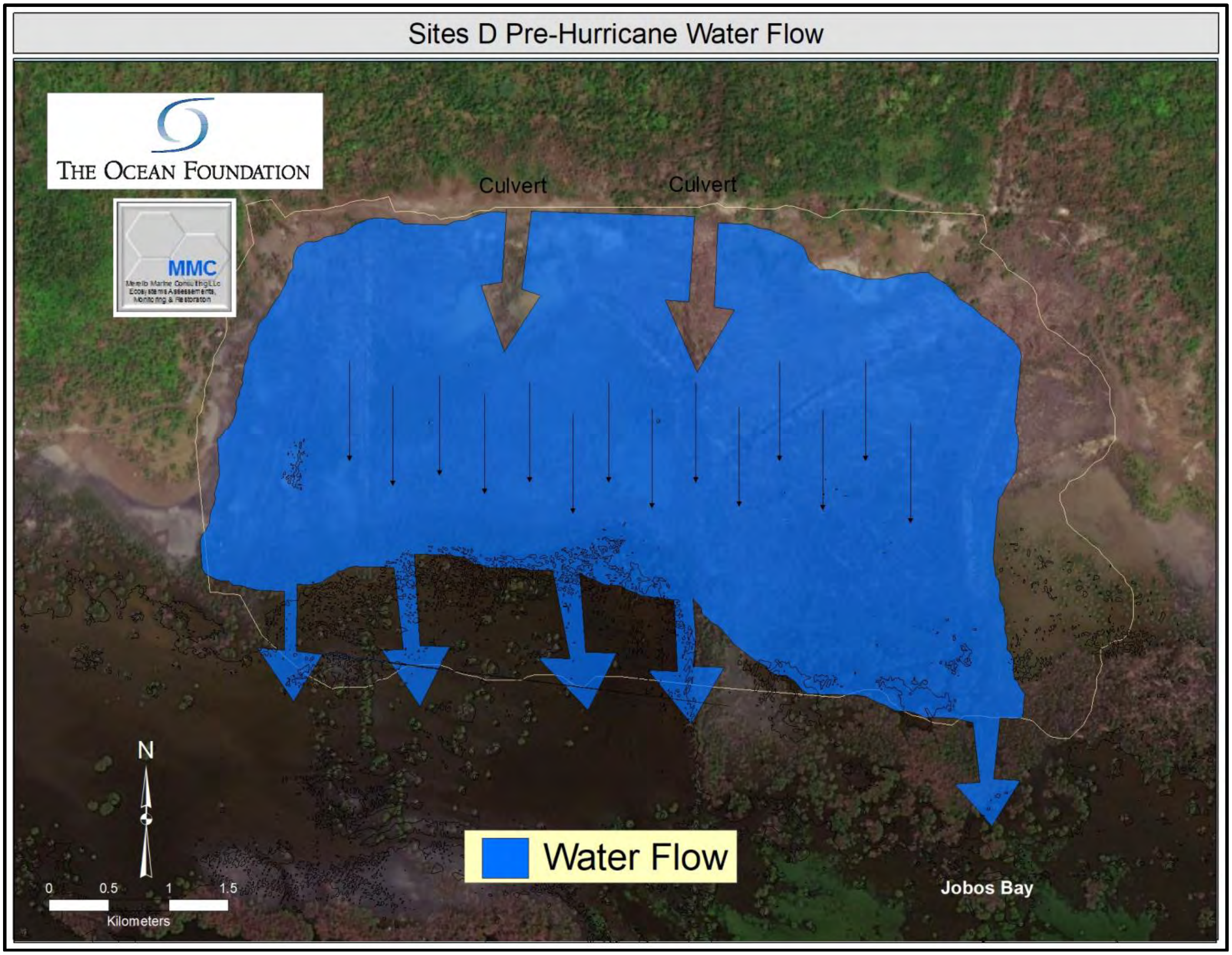


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Figure 4A. Site A restoration area showing water flow restoration activities.

Figure 4B. Site B restoration area showing preexisting channel and proposed extension.

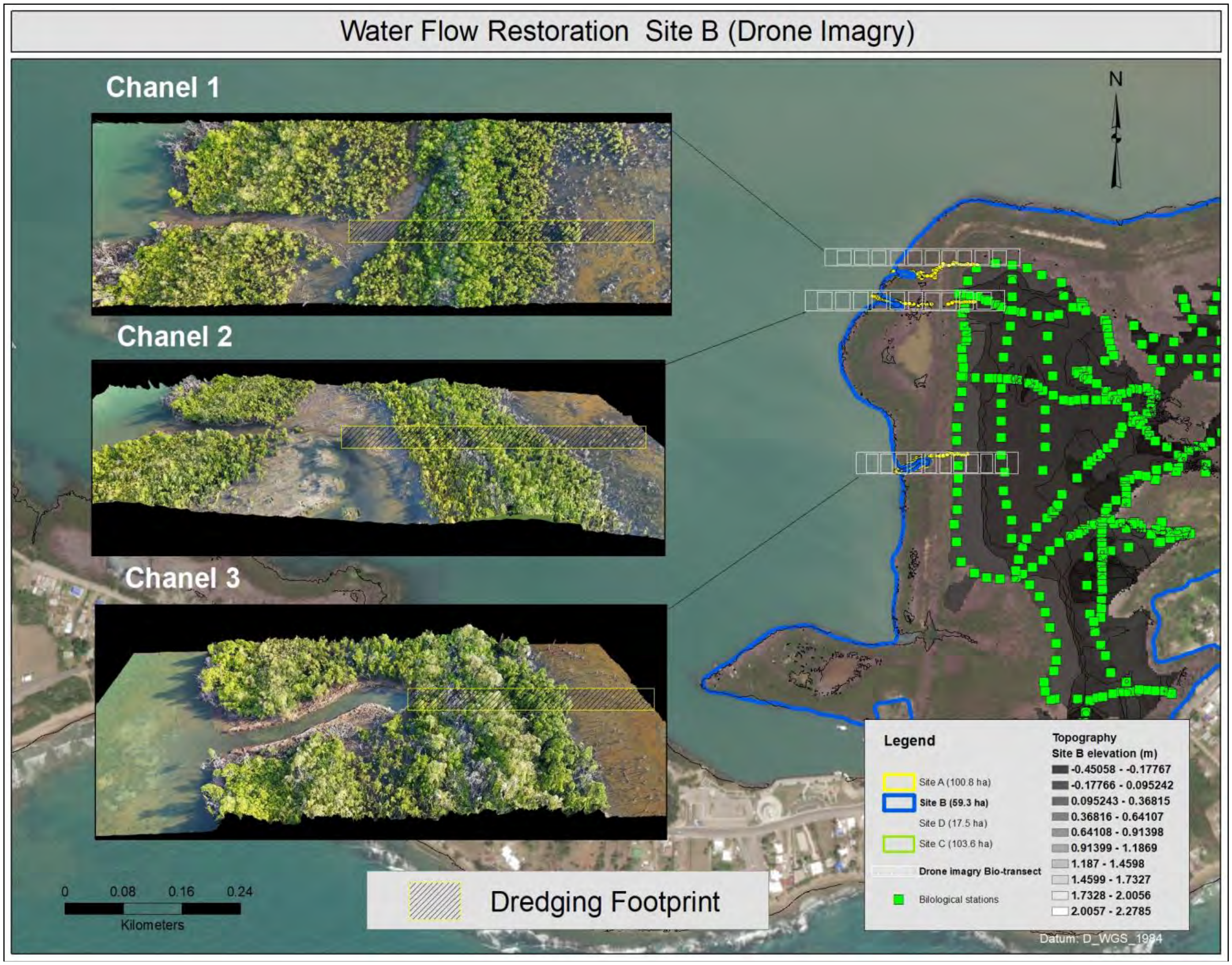


Figure 4C. Site C restoration area showing pre-existing release channel restoration.

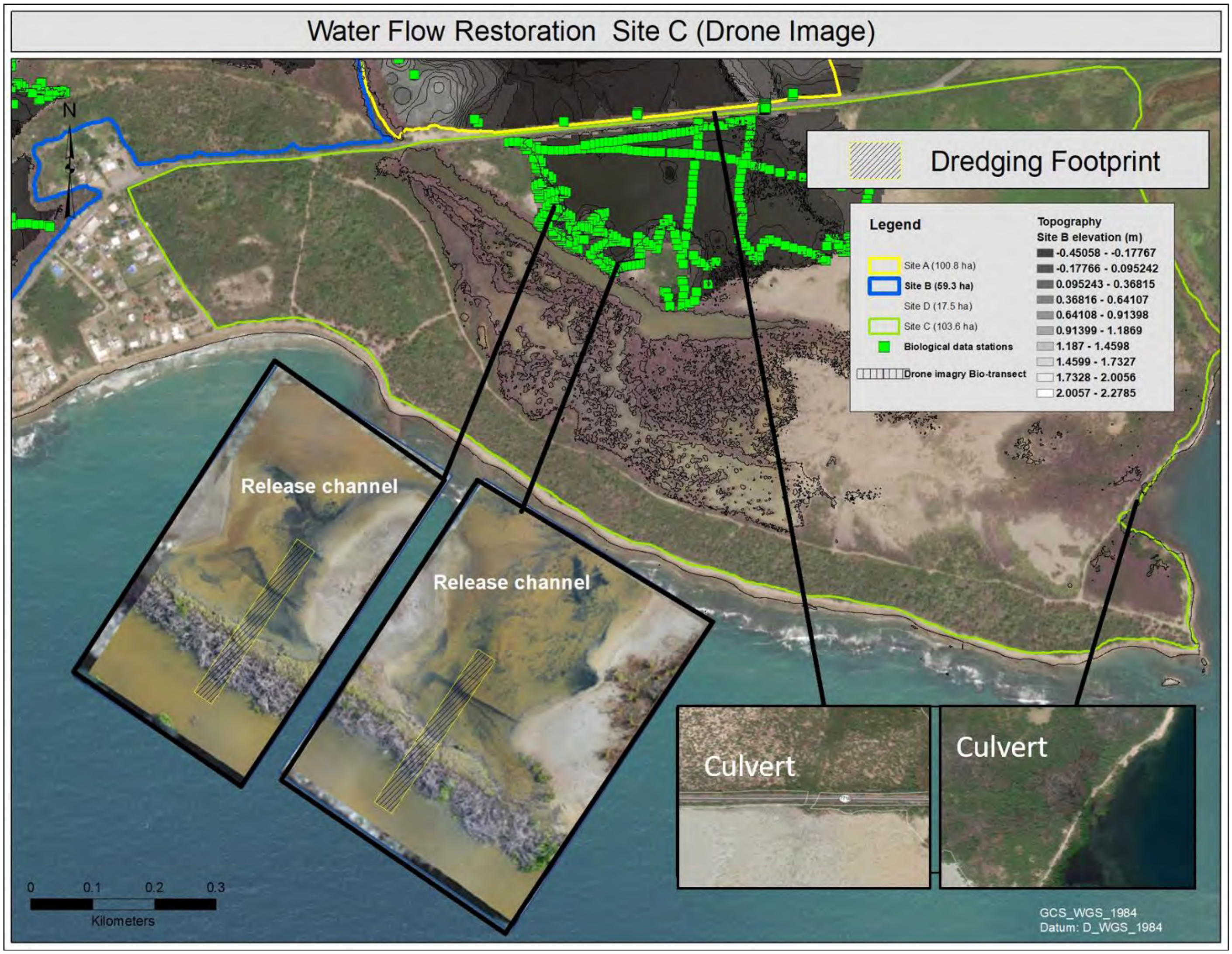


Figure 4D. Site D restoration area showing habitation and relining of s culvert locations.

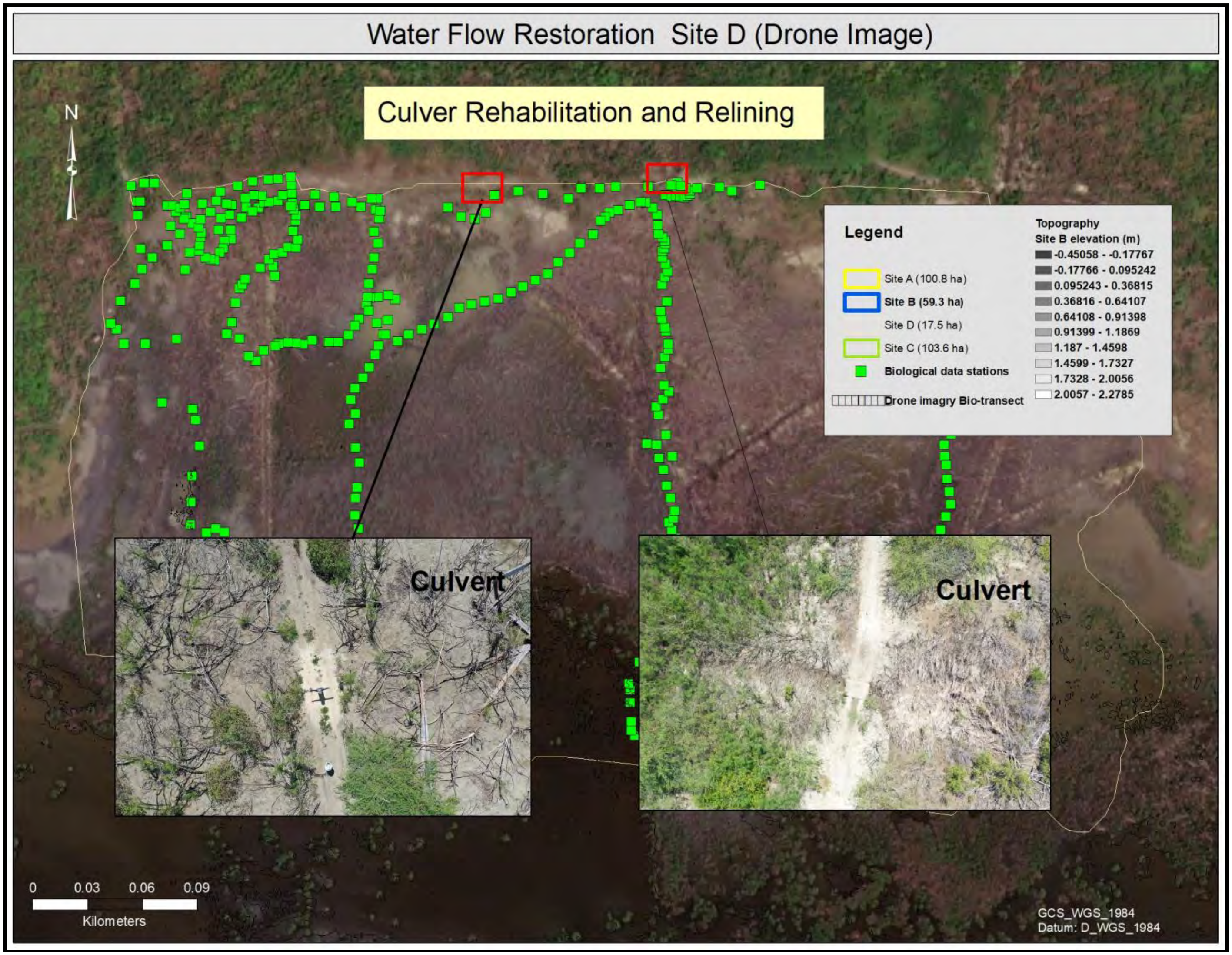


Figure 5A. Site A restoration area showing mangrove SAFE SITES

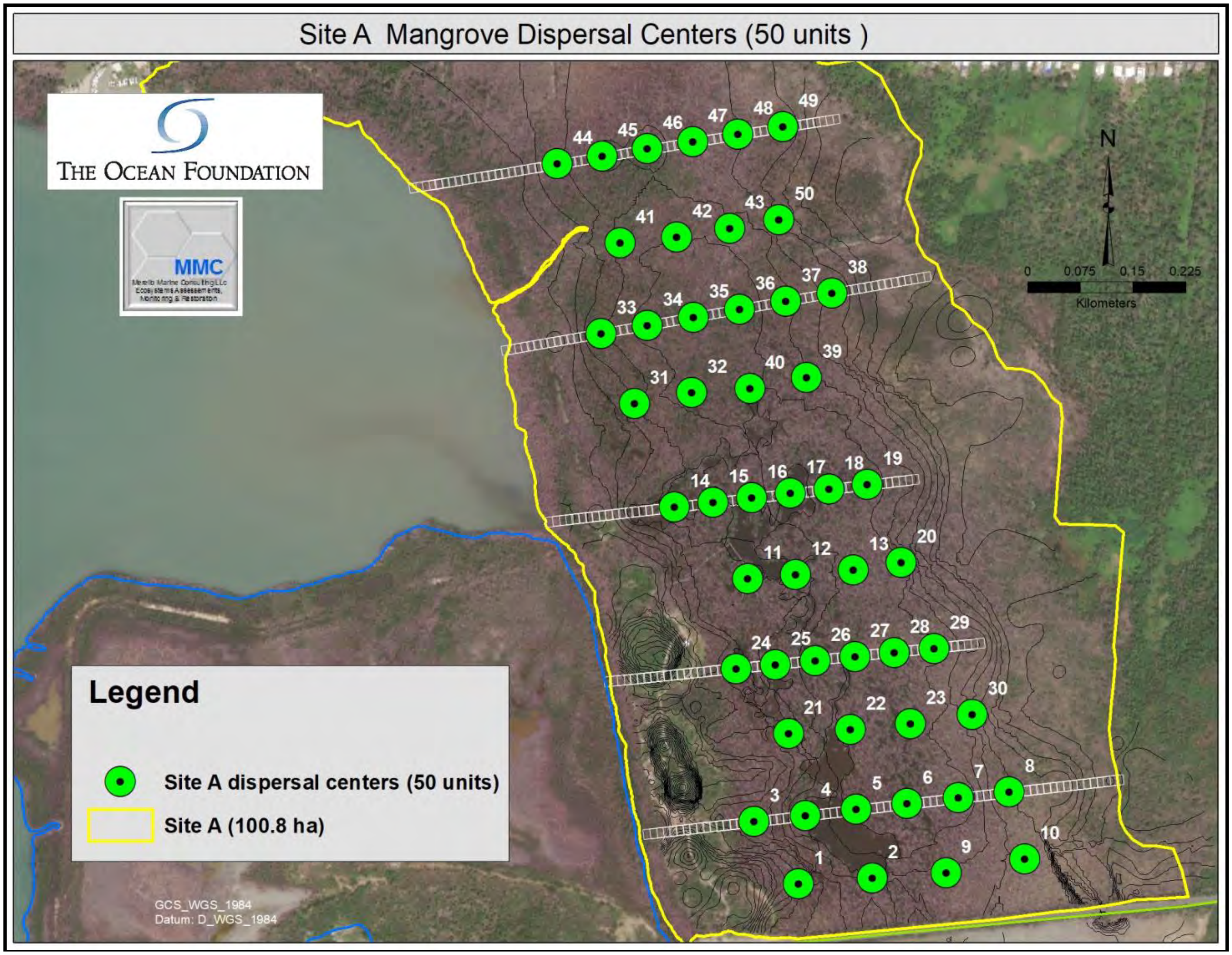


Figure 5B. Site B restoration area showing mangrove SAFE-SITES.

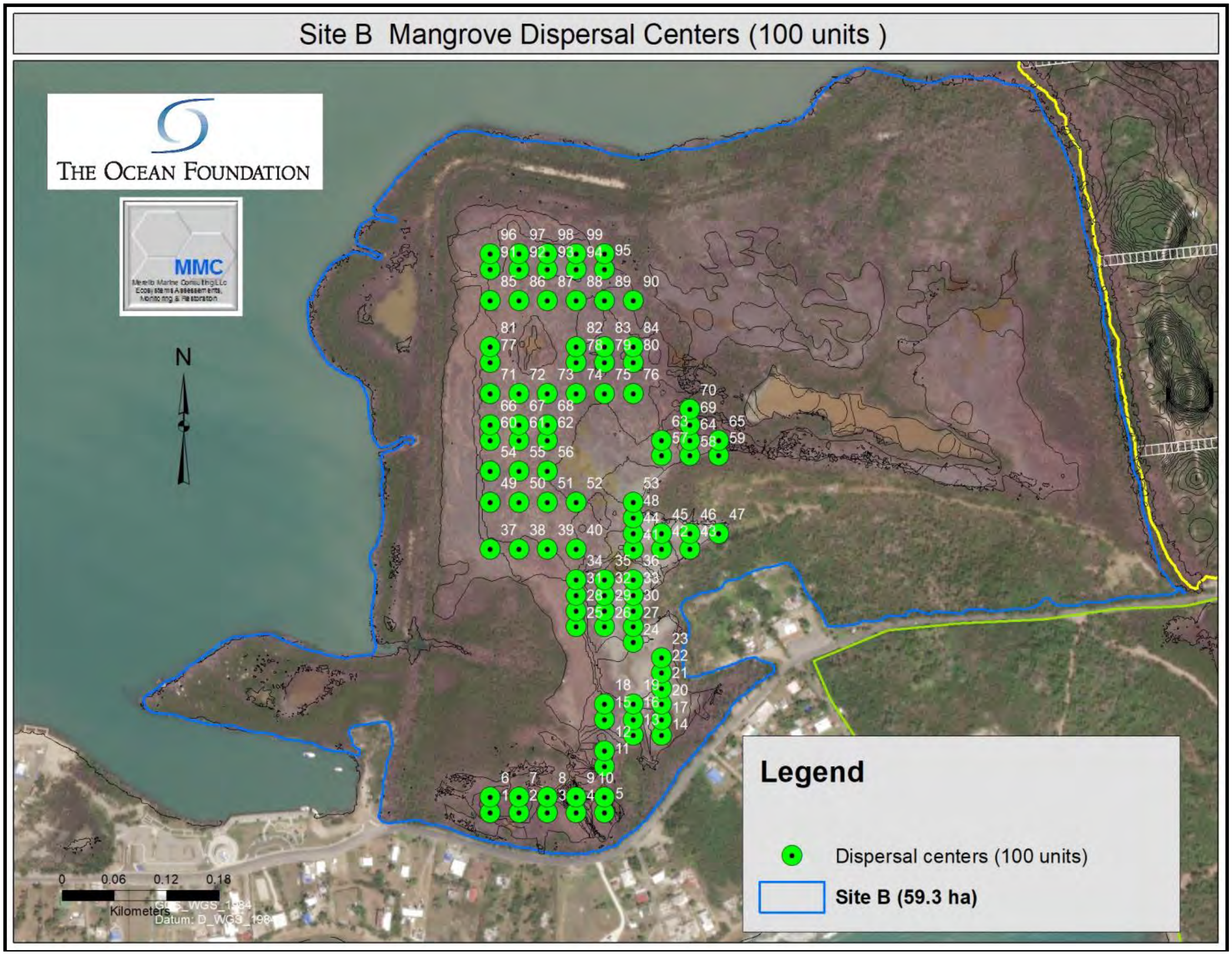
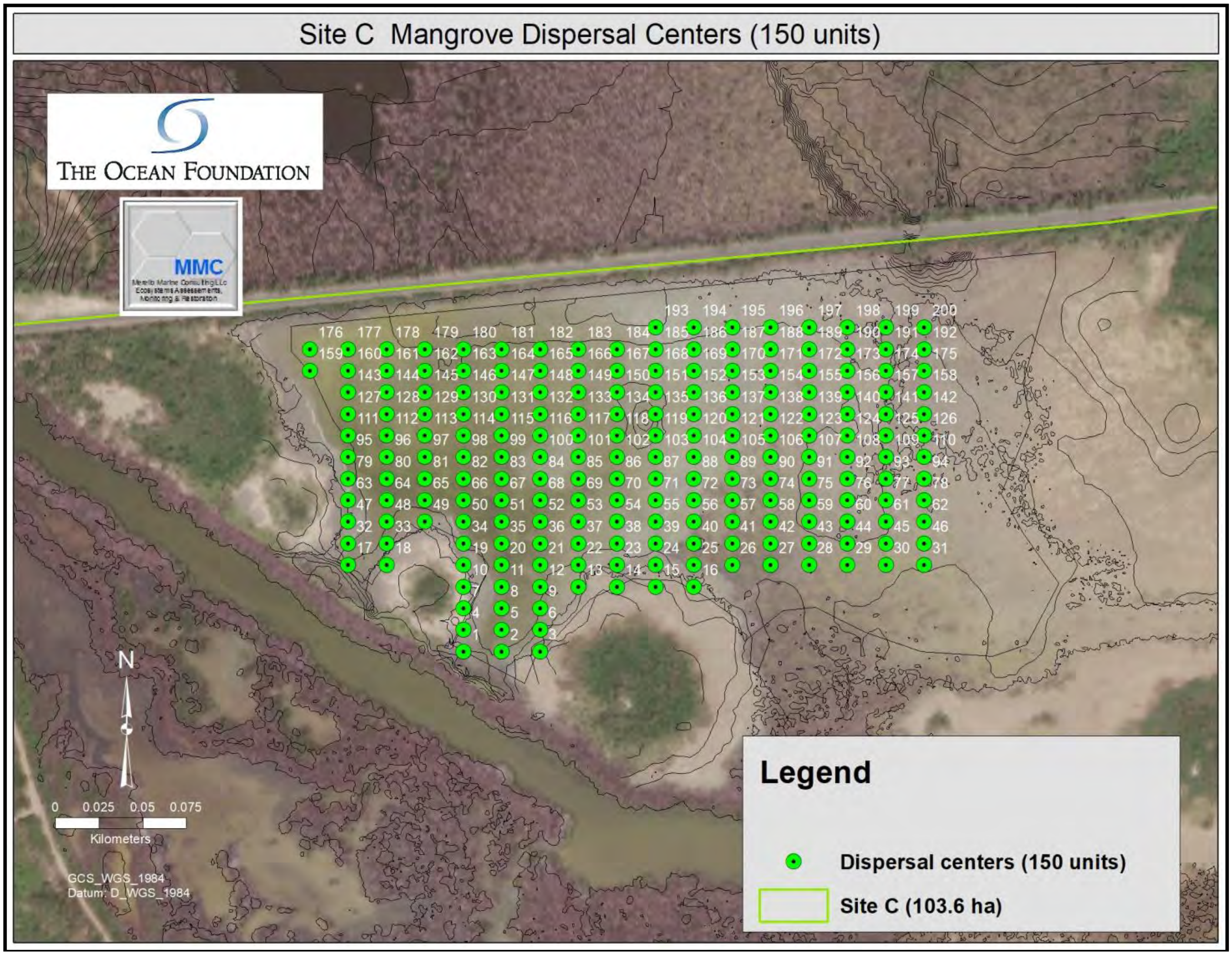


Figure 5C. Site C restoration area showing mangrove SAFE-SITES



Appendix A

Image 1. Mangrove Nursery Site (Located within the property of JBNERR).

Image 2. Dispersal centers.

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