IMPROVEMENT AND CONSTRUCTION OF THE METRO SAN JUAN BARRIER CORAL REEF: A HAZARD MITIGATION PROJECT
Section 404 Hazard Mitigation Grant Program
August 24, 2020

1. Project location

The location of this project will be along the barrier coral reef system located 0.5-1.0 km offshore from Punta Las Marias in a westerly direction to Puente Dos Hermanos, Condado, San Juan, Zip Code 00911 (Figure 1). The area of reef to be improved will be a subset along the shallow portions of this system which has an overall approximate length of 5 km.

2. Project location:

The approximate boundaries of the identified area are:
18.468 N, -66.084 W
18.464 N, -66.084 W
18.465 N, -66.036 W
18.457 N, -66.036 W

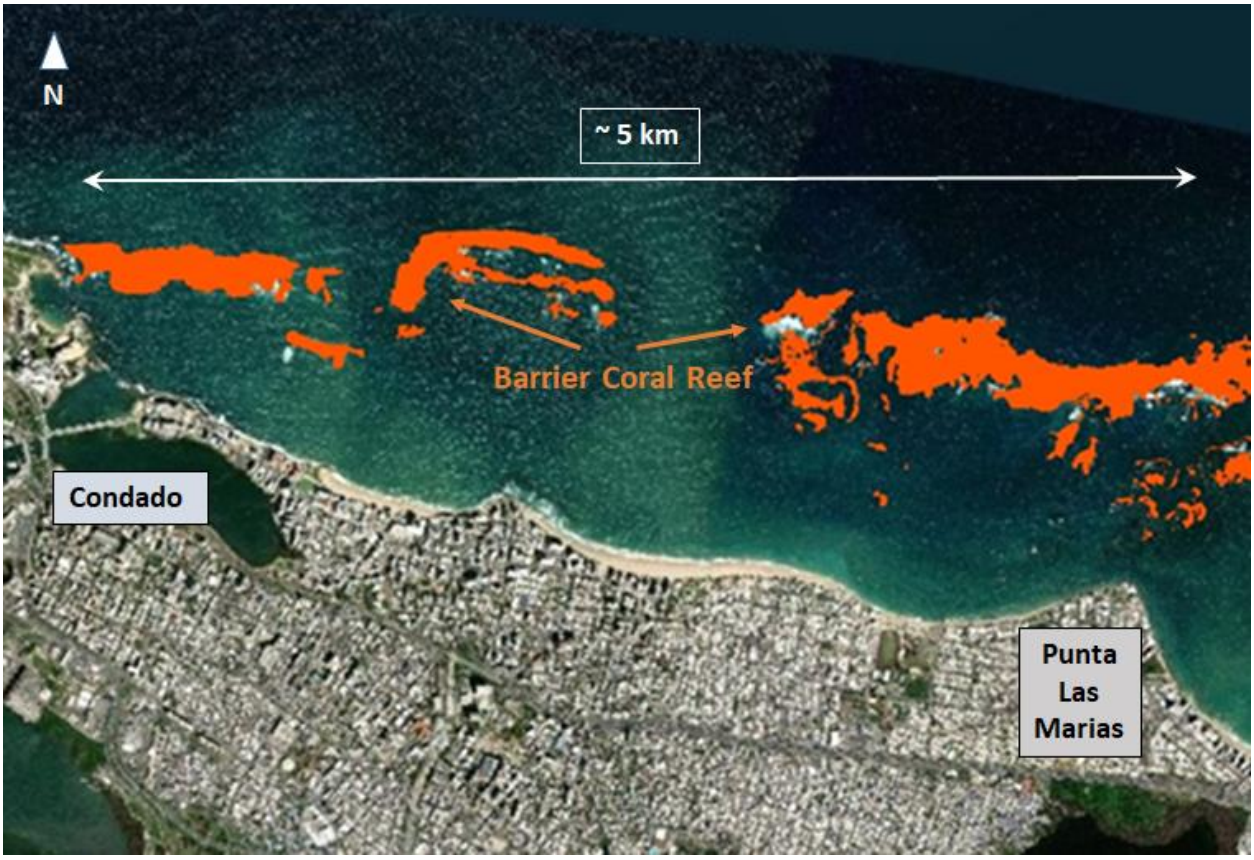


***Figure 1**. Map of project location between Punta Las Marias and Codado showing shallow offshore barrier reef in orange.* ***Latitude, Longitude**:* 18.464N, -66.050W ***Cadastre Number**: 041-032-140*

3. Description of Existing conditions

Coral reefs serve as Puerto Rico's first line of defense against storm wave energy and coastal flooding by acting as natural breakwater infrastructure. The coral reefs offshore of San Juan have historically provided protection to the valuable coastal infrastructure from storm waves. The three-dimensional structure of live coral reefs (hereafter structural complexity) plays a crucial role in dissipating wave energy and protecting the coastline[1]. Compared to other more near shore reefs, the San Juan barrier reef is in much better condition with sections having abundant live coral and therefore functioning to protect the coast.

***Figure 2.** Aerial view of natural reefs dissipating wave energy offshore of San Juan.*

For example, the Dominos reef off San Juan is the station with highest coral cover in the 42 stations of the Puerto Rico Coral Reef Monitoring Program managed by DNER (Figure 2). During the two hurricanes in 2017 (Irma and María), the reefs attenuated wave energy, reduced the velocity of water from storm surges, and protected coastal communities, real estate and critical public services infrastructure.

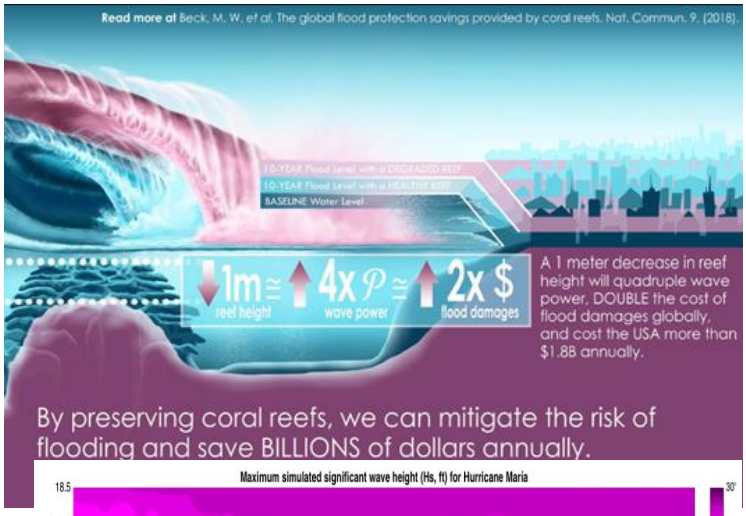
Multiple scientific studies, models, and simulations recognize the critical importance of reef systems in protecting shorelines and property from wave energy[2] (See also Figure 3). Enhancing this system to increase height and structural complexity of the reef to build coastal resilience is a high priority for the Commonwealth of Puerto Rico. The specific coral reef construction design

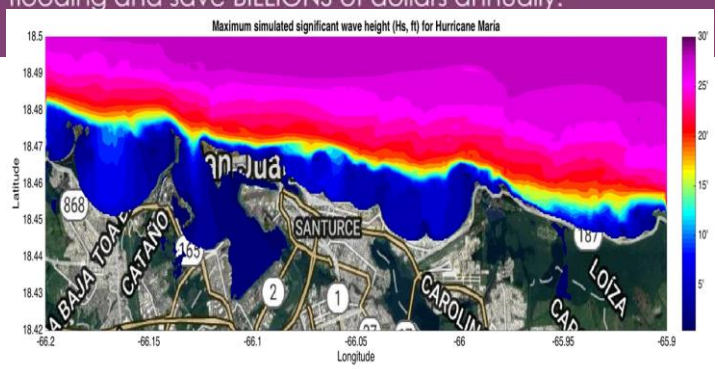
[1] Coral reef structural complexity provides important coastal protection from waves under Rising Sea Levels (2018) Daniel L. Harris, Alessio Rovere, Elisa Casella, Hannah Power, Remy Canavesio, Antoine Collin, Andrew Pomeroy, Jody M. Webster and Valeriano Parravicini. Sci Adv 4 (2), eaao4350. DOI: 10.1126/sciadv.aao4350

[2] The global flood protection savings provided by coral reefs. Michael W. Beck 1,2, Iñigo J. Losada3, Pelayo Menéndez3, Borja G. Reguero1,2, Pedro Díaz-Simal3 & Felipe Fernández3. Nature Communications (2018) 9:2186.)

selected for this project will help prevent the same post-storm damage caused by Hurricanes Irma and Maria (Figure 4).

***Figure 3**. Value of reef height on coastal protection. Coral reefs provide significant annual flood protection savings for people and property. A recent publication from Beck, et. al. (2018) articulates the value of reef height on coastal protection.*





As a strong category 4 hurricane with maximum sustained winds of 155 mph, Maria moved west-northwestward over southeastern PR into the interior and northwestern PR. Widespread hurricane force winds spread all over mainland PR along with extremely heavy rainfall that produced major to catastrophic flooding and flash flooding, especially across the northern half of Puerto Rico. In addition, the maximum storm surge in San Juan was 2.35 ft. (https://www.weather.gov/sju/maria2017). This combination of uniquely severe factors caused widespread property and road damage along the entire coast of Puerto Rico. While the coral reef offshore of San Juan did provide significant shoreline protection in 2017 (Figure 4), additional reduction in coastal flooding risks will be provided by constructing the reef improvement project proposed here.

***Figure 4**. Wave height/energy reduction is demonstrated by simulations of actual hurricane induced wave height (red) and reduced energy due to the presence of the coral reef (blue).*

Coastal communities in the San Juan Metro area were protected from direct wave attack by coral reef natural infrastructure with coastal floods only temporarily affecting socio-economic activities at Condado, Punta Las Marias and Ocean Park (Figure 5). . Major

floods of the San Juan Metro area were associated with intense precipitation affecting the area during hurricane Maria, failure of stormwater management system (flood control pumps) and poor maintenance of storm drains. More protection from coastal flooding will be provided by constructing the proposed project to improve the function of this reef in reducing wave energy. Additionally the wave attenuation provided by these coral reefs promotes the accretion of sand on the beaches in between storm events which supports overall coastal resiliency.

Figure 5. *San Juan municipality crew clearing sand and reopening public road access after storm floods and sand deposits (2017).*

The goal of the proposed work is the improvement of the San Juan (SJ) coral reefs to mitigate and lessen the frequency and severity of flooding and coastal erosion. Constructed reef structure will improve the existing natural barrier protecting the coast, averting flood inundation and reducing beach erosion rates. This will protect a high density/populated coastal area of approximately 80,000 people with a hospital, 3 schools and other public infrastructure. As seen in Figure 6, there are many public and private structures in the San Juan metro area that need protection. This hazard mitigation project can reduce flood risk and lessens response and recovery resource requirements after a disaster (Figure 7). The most important structures for commerce are the San Juan Bay Port and the largest international airport on the island. The hospital, nursing homes, and treatment centers were particularly vulnerable to the severe storms. The water treatments plants are crucial to maintain water service to the population before and after storms. Historic and cultural sites that are protected by federal and local laws are also present in the San Juan metro area and should be protected from future flooding. Tourism facilities bring economic activity that is essential to the overall economy and to the individuals who depend on it. The specific design being chosen for this project should help ensure that flooding damages are reduced in the future.

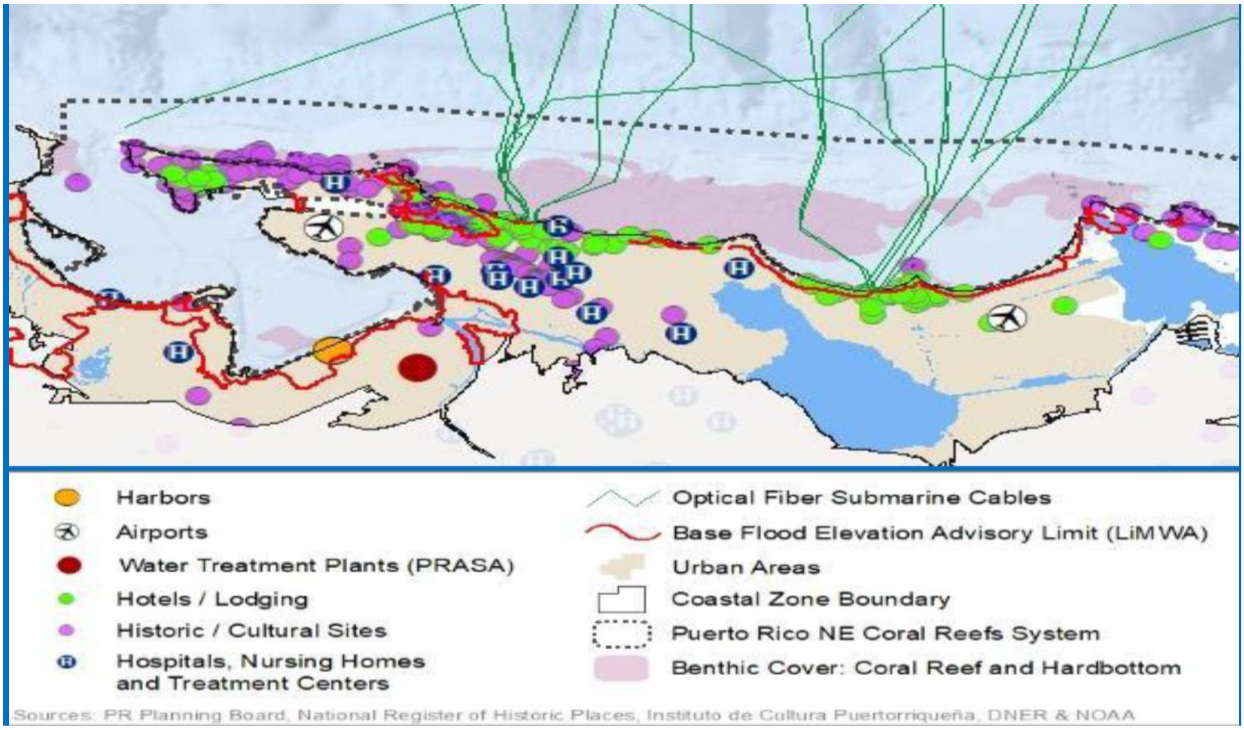


***Figure 6**. San Juan public and private coastal assets at risk (source: PR Planning Board, DNER/NOAA)*

***Figure 7**. Evidence of severe erosion episode affecting public and private assets in Ocean Park, San Juan after the offshore reef system (that is proposed to be repaired by this project) was damaged. (2019)*

In 2018, a study was completed to provide the economic valuation information for Puerto Rico's reef-associated tourism and recreation. The economic impact analysis report revealed that reefs using visitors to Puerto Rico spend over $1.9 billion annually within Puerto Rico. The visitors spend most heavily in the service sector, with lodging, food and beverage and transportation being the three largest expenditure categories. Further, these expenditures support over 3% of jobs, account for nearly 4% of total income to the region and generate nearly $2 billion in economic output to Puerto Rico.[3]

4. Proposed project alternatives

This project seeks to reduce storm damage to public infrastructure and real estate along high risk coastal areas in San Juan. The coastal segment of the San Juan metro area that would be protected from storm inundation, direct wave impact and coastal erosion has approximately 500 assets with estimated value of approximately $2.7 billion[4] (USACE 2020). This project will reduce coastal hazards to community residents, business owners, and workers' in this high-density coastal community. Tourism, recreation and fishing economic sectors will benefit by reef improvement resulting in job creation.

The following coral reef improvement and construction alternatives are considered to examine the future without project (No action) as well as three (3) options to provide hazard mitigation from coastal flooding to the infrastructure in the project area. The 3 action options are intended to provide coastal protection benefits through the reduction in wave energy to the coastal system, effective protection of communities, public/private infrastructure and livelihoods. The 3 alternatives differ in the timing in which the project will provide maximum benefit in wave attenuation and long-term adaptability to sea-level rise. The preferred alternative provides both immediate benefit and long-term adaptation to sea-level rise; whereas the other alternatives do not.

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[3] Leeworthy, V.R., Schwarzmann, D., Hughes, S., Vaughn, J., Dato, C., and Padilla, G. (2018) Economic Contribution of Reef Using Visitor Spending to the Puerto Rican Economy. Silver Spring, MD: Office of National Marine Sanctuaries. National Oceanic and Atmospheric Administration.

[4] Puerto Rico Coastal Storm Risk Management Study: Integrated Feasibility Report and & Environmental Assessment (USACE 2020).

The options were developed considering existing viable approaches and technology to improve the coral reef natural facility by increasing the 3-dimensional physical structure and increasing "roughness" that dampens wave energy across the reef. All options considered would require completing a final design phase to calculate detailed parameters (optimal construction footprint location and dimensions; structure design and stability; coral propagation plan). Construction of a breakwater structure on the reef was not considered as this would be precluded by jurisdictional and federal permitting, environmental compliances, construction logistics and cost.

The following 4 options are considered:

1. The combined deployment of artificial coral-like hybrid cement structures with the addition of native coral to increase roughness and sea-level rise adaptability.
2. The deployment of only native corals.
3. The deployment of only artificial cement structures.
4. The no-action alternative.

Alternative 1 (Prefered): Hybrid artificial structure and coral deployment (gray/green)
This alternative will combine specially designed wave attenuation structures with a naturally occuring coral type that is known to maximize shoreline protection. This will rapidly increase the existing reef roughness height by ~.5 meter to strengthen its natural barrier and wave attenuation capacity, which will increase over time as the corals continue to grow. This will be accomplished by implementing a multi-method hazard mitigation approach. First, the roughness of the reef will be rebuilt with artificial coral mimicking cement structures. Second, a coral that thrives in high-energy environments will be affixed adjacent and between the cement structures to allow for a gray/green wave attenuation barrier that mimics the natural protection provided by healthy coral reefs. The coral Elkhorn Coral (*Acropora palmata)* is the selected species for quickly increasing reef roughness based on its rapid growth, large branching physical structure, solid reef building skeleton and well tested propagation methods. This coral is the primary coral species growing on the reef crest and contributing to reduce wave energy and protect coastal areas against storm waves and flooding. Third, smaller fragments of the same coral will be adhered directly to the artificial structures allowing even the artificial components to "grow" overtime ensuring the benefits last well into the future, even as sea level rises. The details of this strategy are outlined below.

Specially designed wave attenuation structures precast in cement (~0.5 m, ~35 kg--See Figure 12) and the wave breaking elkhorn coral will be placed and secured to the shallow (2-3m) hard bottom areas of the reef. This will occur at multiple segments selected to maximize wave attenuation along the ~5 km of the reef system in the project area. In total 8 segments totaling ~1.2 km are proposed. Each segment will be between 200 and 700 meters long and ~20 m wide. Based on preliminary modeling in order to maximize wave attenuation each segment will be configured (Figure 9) with one seward row with only corals and one shoreward row with structures and corals (Figure 10); These will be oriented with the east-west long axis of the reef. The row consisting of artificial structures and corals will be configured at a density of ~ $0.5/m^2$ and the coral only row will be configured at approximately one meter centers (~$1/m^2$ density)(Figure 11).

This placement configuration maximizes wave attenuation benefits based on results from hydrodynamic modeling on the effects of increasing reef roughness with artificial structures and corals. The artificial cement structures will be constructed to withstand hydrodynamic forces, mimic natural coral and be secured to the bottom with steel anchors and/or cement. Live corals produced from coral propagation facilities are secured to the reef bottom, using well established techniques, and to the artificial structures within the footprint to grow to a height of approximately 30-50cm over the project period and will continue to grow and provide additional benefit well into the future. This hybrid approach has the benefit of providing a rapid increase in reef roughness from the artificial structures and will continue to acquire roughness as the corals grow and produce carbonate material, therefore increasing reef crest elevation (Figure 15). The end product will be an actively growing structure that continually deposits hard concrete-like coral material on the reef to promote accretion of the natural reef structure and adapt to rising sea-level. The coral mimicking wave attenuation structures will be covered with coral over time to enhance the wave break benefits of the coral reef as it actively grows. This alternative is the only one that quickly returns the reef to better then its pre-2017 condition and at the same time will ensure the action keeps up with sea level rise.

Details on the design, methods and construction of the preferred alternative are provided in **Section 7. Scope of Work**.

Alternative 2: Deployment of corals only

This alternative would increase reef roughness over time by deploying corals to grow over hard bottom areas. Corals produced from propagation facilities are secured to the reef in dimensions and density as described above. Live corals that have been produced as part of the project are secured to the reef bottom within the footprint (~1/m^2), to grow to a height of approximately 30-50cm over the project. Corals will be secured to the shallow (2-3m) hard bottom areas of the reef along an approximately ~1.2 km long band (~20 width) oriented with the long east-west long axis of the reef. The coral are placed at approximately one meter centers (~1/m^2 density). This will provide for an increase in reef roughness and wave attenuation over the long-term but will not produce the rapid benefits in as timely of a manner as Alternative 1 since the corals will require time to grow.

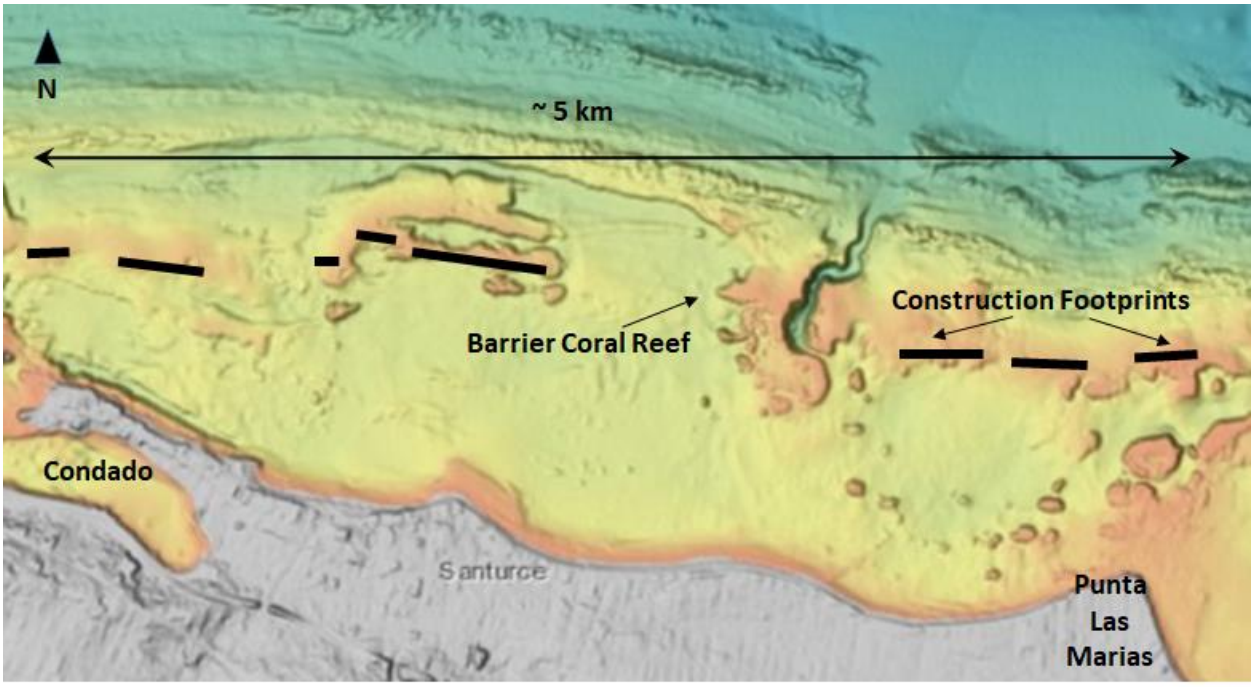
Alternative 3: Artificial structures only

Artificial structures are secured to the reef in a configuration, dimensions and density as described above. This will provide for an increase in reef roughness and wave attenuation. This alternative would provide an increase in reef roughness and wave attenuation benefit. However this alternative will not provide for the continual accretion and long-term deposition of carbonate material on the reef and limit the capacity of adaptation to sea-level rise and would require long-term modifications and maintenance. Also the multiple socio-economic services of having a growing coral reef will not be obtained. The benefits provided from this approach will be greatest at time of implementation and fade over time as erosion and breakdown of the structures takes place. The opposite is true with alternative 1 where the benefits continue to increase over time. This alternative is also expected to face major permitting challenges as generally the

placement of artificial structures (without incorporation of live corals) on coral reefs is generally not authorized.

Alternative 4: No-action
The no-action alternative will maintain the hurricane damage and loss of wave attenuation for the long-term. In the best case, the coral recovery will require multiple decades on its own or may never recover to pre-hurricane condition. Therefore, the San Juan barrier reef will be less likely to attenuate wave energy, reduce the velocity of tidal water from storm surges, and protect coastal communities, real estate and critical public services infrastructure. This will leave the San Juan metro area more vulnerable to future storms then it was in 2017 before the Hurricanes. Additionally the socio-economic services of an improved coral reef will not be obtained. The consequences of choosing the no action alternative are expected to compound over time.

5. Project drawings



Figures 8*. Bathymetry map (depth) of the project area, warm colors (orange) are shallower areas (~2 m) and cool colors (green) deeper areas (~10 m). Black lines represent approximate locations and footprints where artificial structures and corals will be constructed on the reef to increase roughness over the shallow coral reef.*

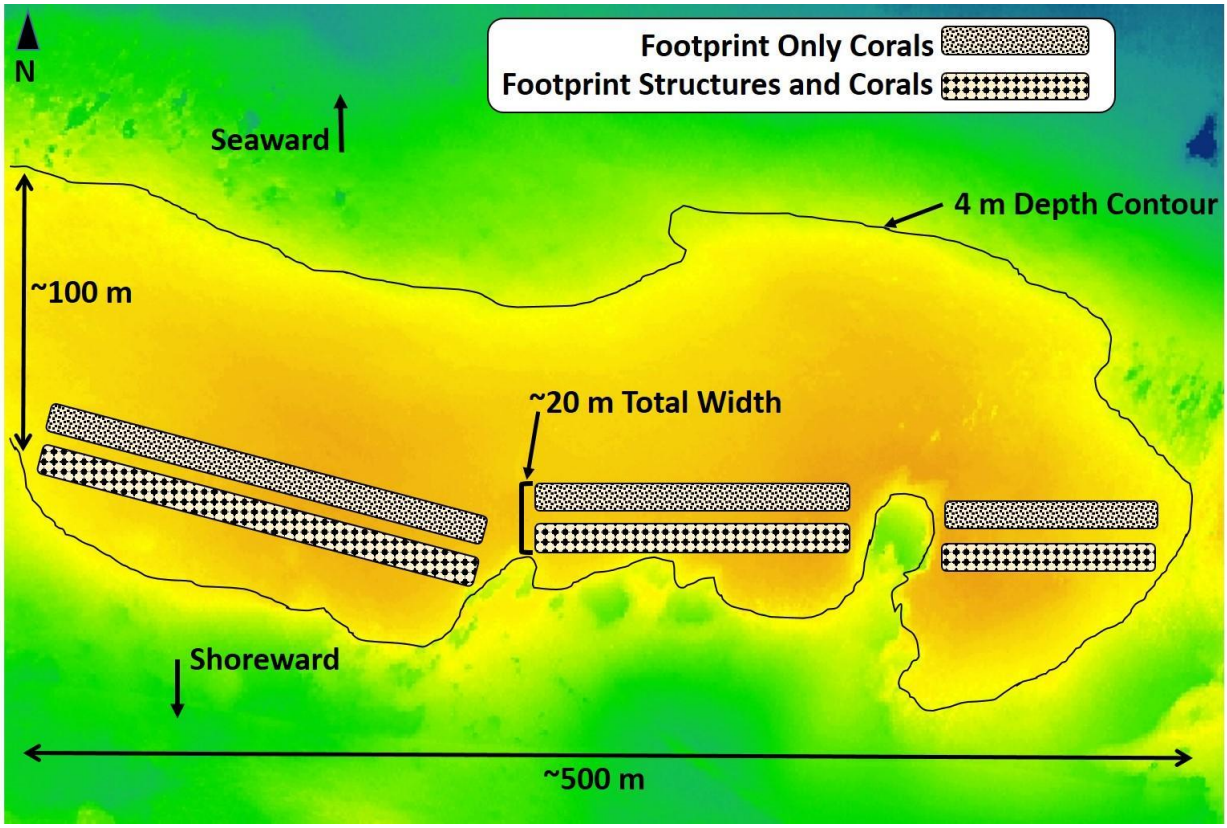


Figure 9. *Depiction of typical shallow hard bottom reef showing plan of construction footprints from the preferred alternative over the bathymetry data. The orange colors are shallow (2-3 m) and the green colors are deeper (5 m). The two components of the footprint are shown, bands with structures and corals (coarse texture); and bands with high density corals (fine texture).*

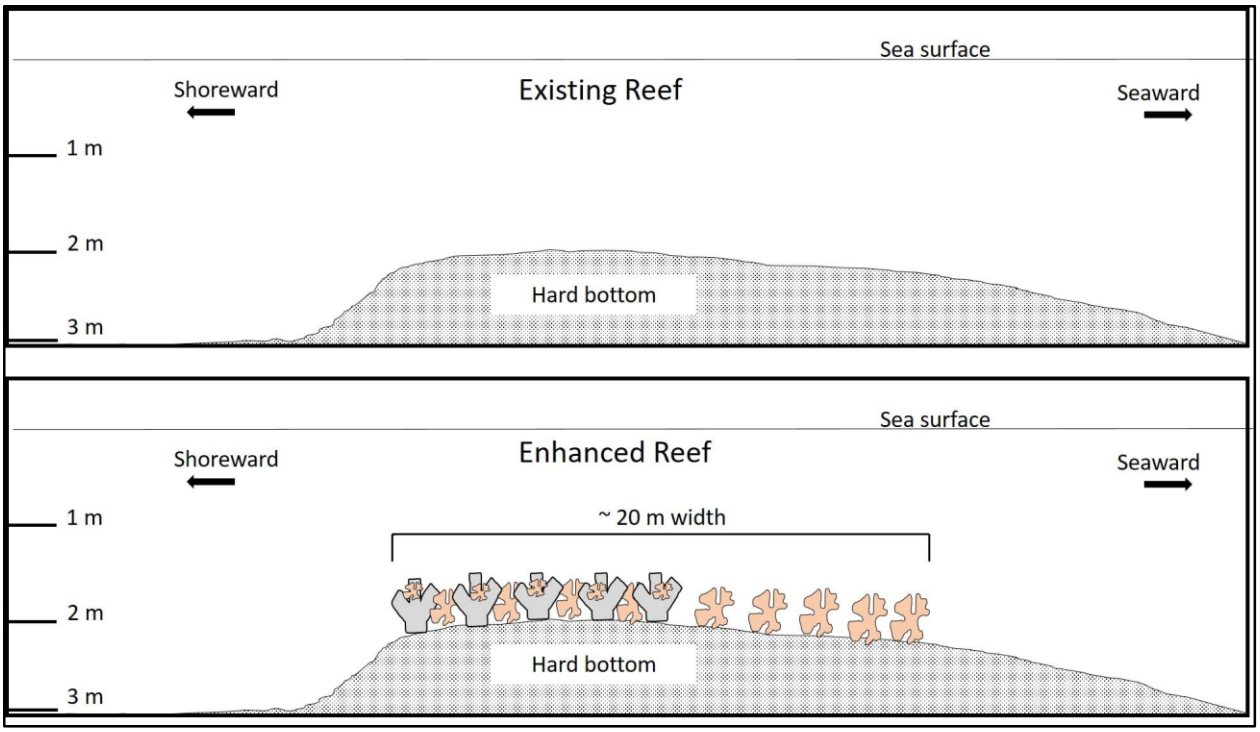


Figure 11. *Profile view of typical cross section showing reef before contruction (Top) and after artificial hybrid structures and coral are secured to reef (Bottom).*

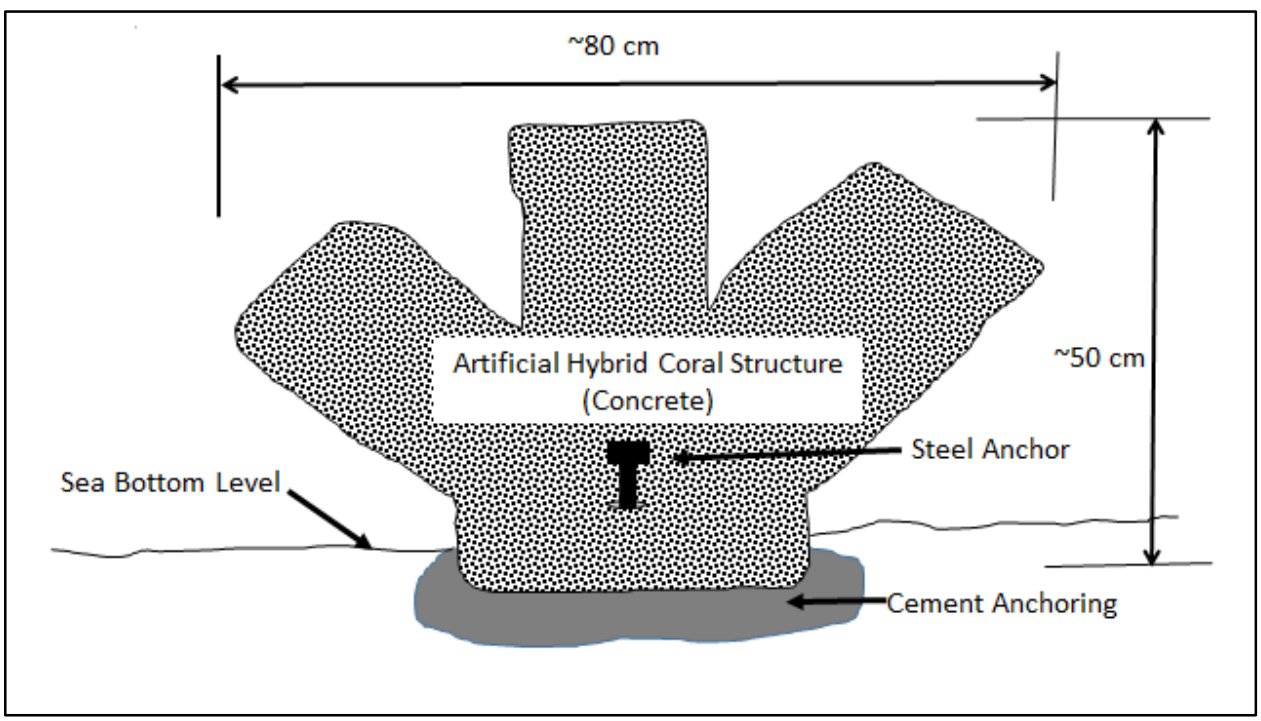


Figure 12. *Schematic of potential prototype design of artificial coral concrete modules.*

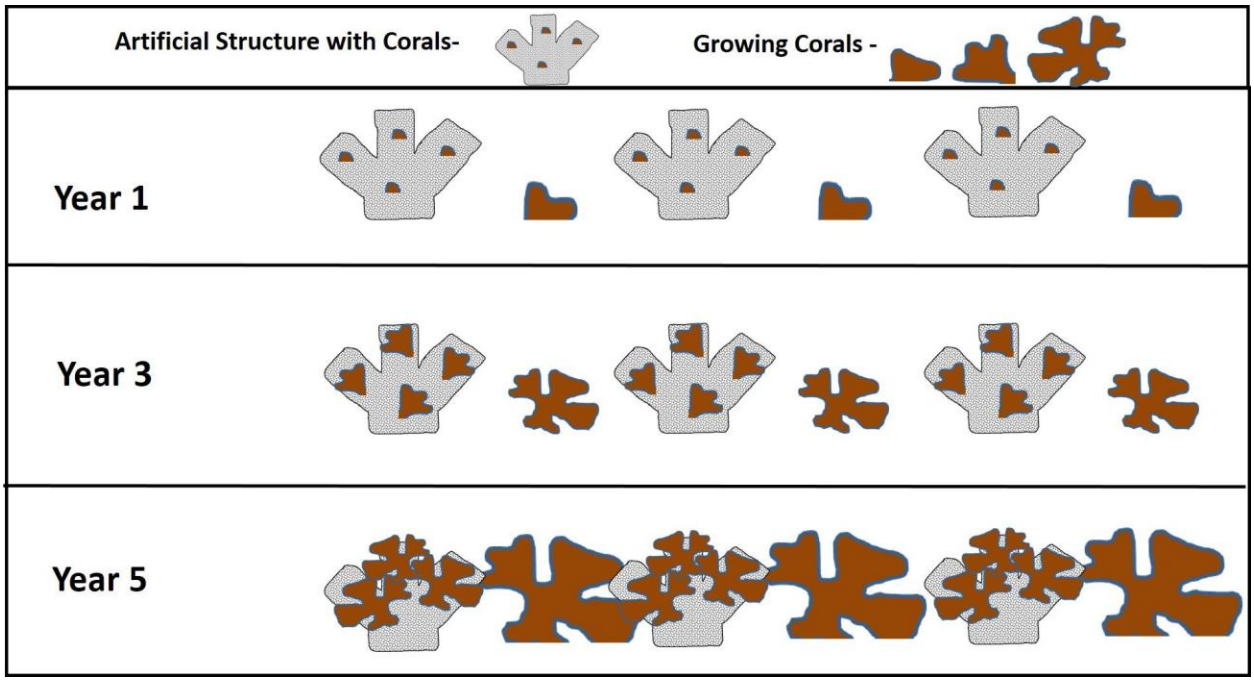


Figure 15. *Side view of the artificial structures and corals showing growth of corals and increased roughness over time.*

6. Project Photographs

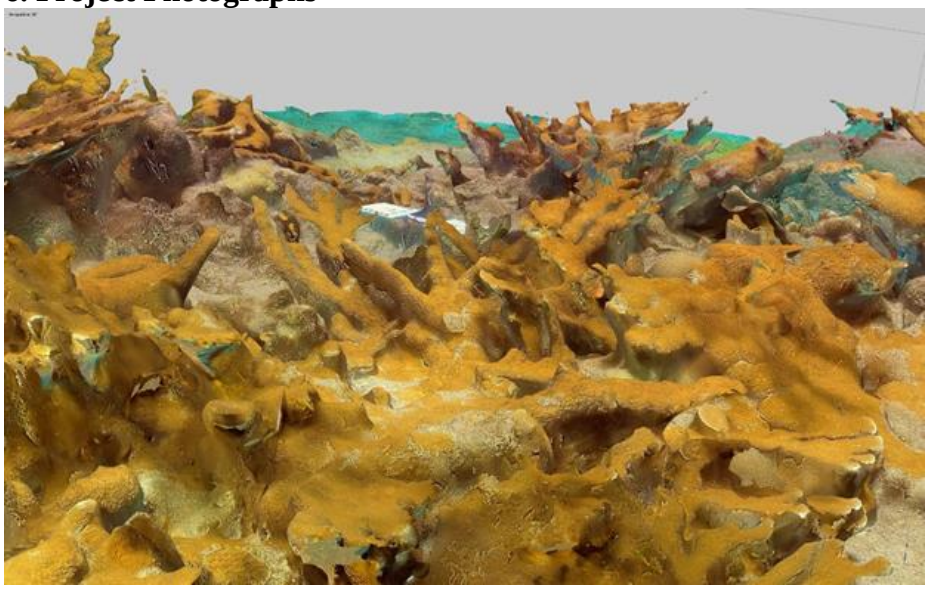
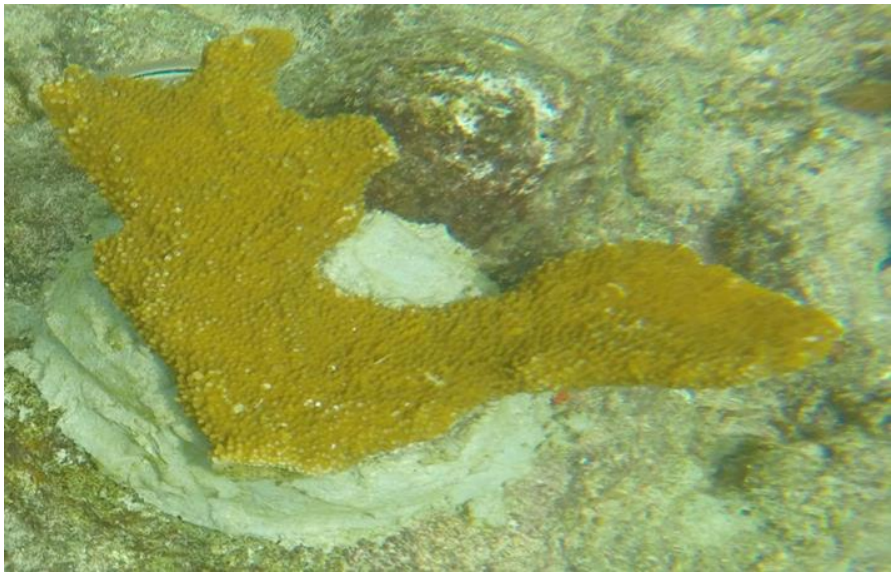
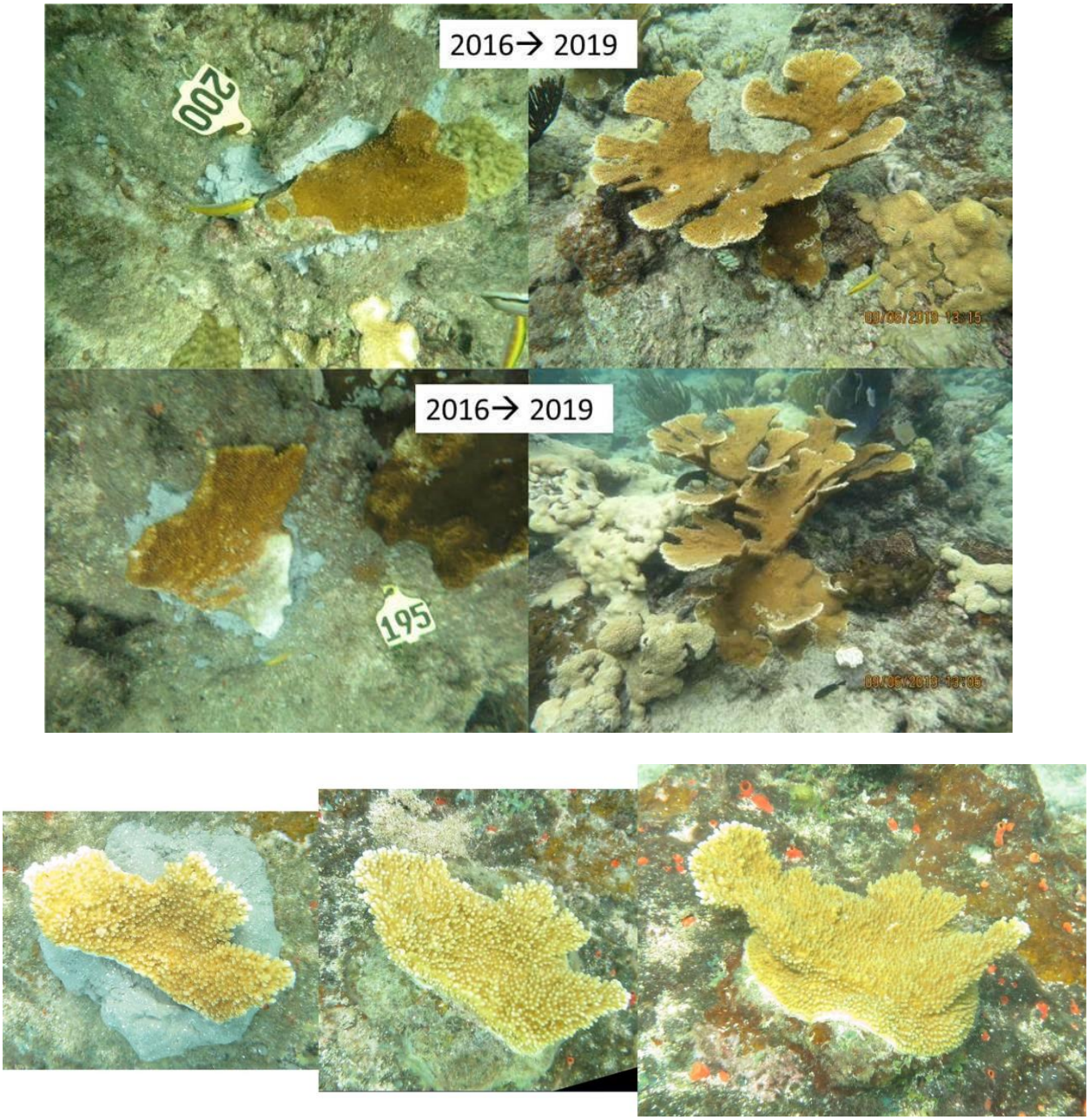


Figure 16. *3-dimensional photomosaic image of typical reef with increased roughness provided by coral and resulting wave attenuation capacity at Dominos reef offshore of Ocean Park, San Juan. (NOAA Tech Memo). This reef was not impacted by the 2017 Hurricanes to the same degree as the reefs proposed in this project.*

Figure 17. *Photographs of high coral density providing wave attenuation capacity at Dominos reef offshore of Ocean Park, San Juan. This reef was not impacted by the 2017 Hurricanes to the same degree as the reefs proposed in this project.*



Figures 18. *Photograph showing how a propagated coral is secured to the hard bottom with cement.*



Figures 19. *Time series examples of corals affixed at reef improvement sites in Puerto Rico, showing 3 years of growth(Top) and 4 months of growth (Bottom) .*

Figure 20. *Example of the coral grow out structure used to grow A. palmata corals for subsequent placement at reef improvement sites for increasing reef roughness .*