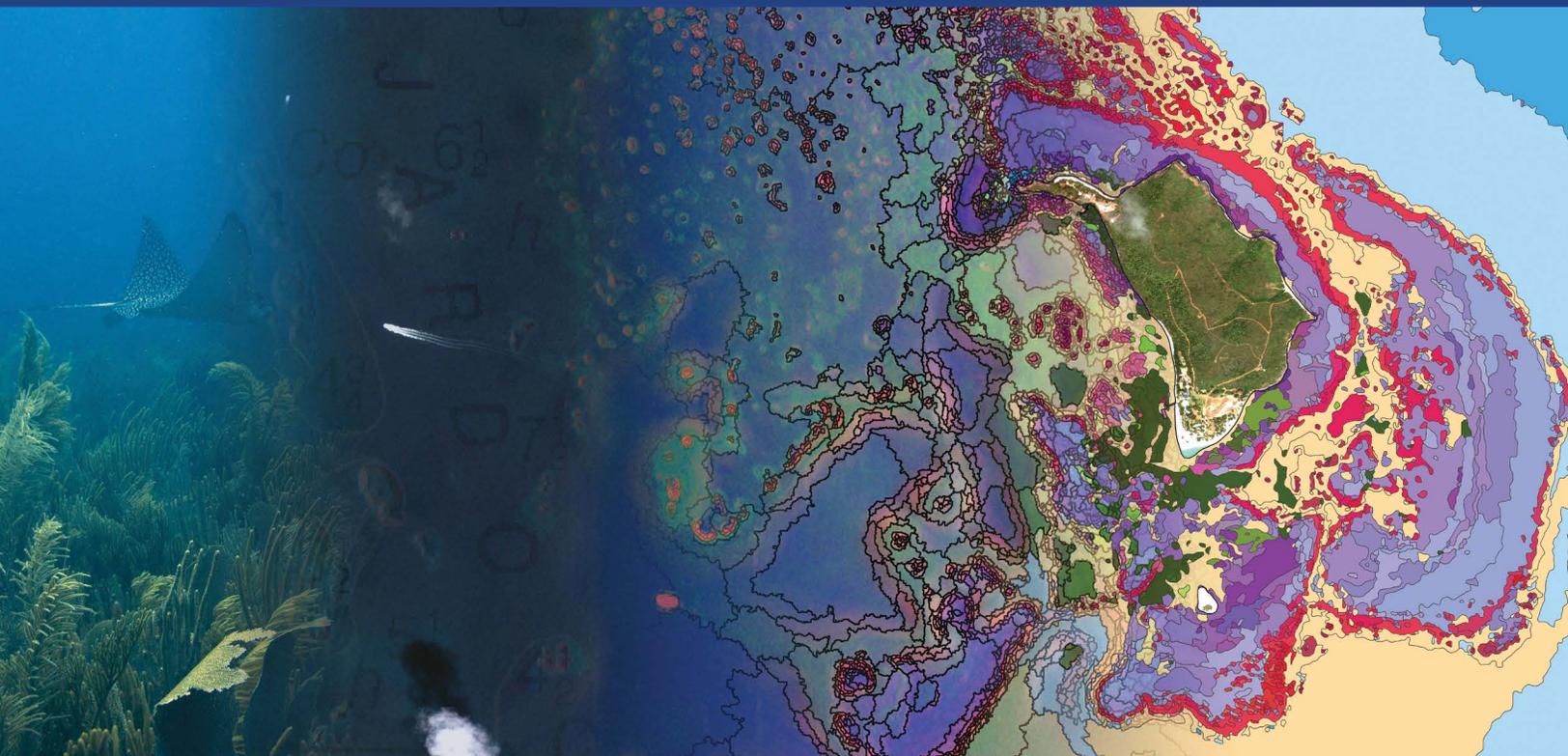


Shallow-Water Benthic Habitats of Northeast Puerto Rico and Culebra Island



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ABOUT THIS DOCUMENT

This report describes the development and assessment of shallow-water (0<35 m) benthic habitat maps for Northeast Puerto Rico and Culebra Island. The objective of this effort, conducted by NOAA's National Centers for Coastal Ocean Science (NCCOS) in partnership with the Departamento de Recursos Naturales y Ambientales (DRNA), was to provide spatially-explicit information describing the benthic habitat types and live coral cover present in and around the Northeast Reserves, a region selected by local managers as a priority area. The habitat map, generated using a combination of semi-automated classification and visual interpretation techniques, represent the first digital maps that describe nearly 100% of the seafloor in the area. The effort also marks the first time a high resolution satellite mosaic representing the seafloor has been provided for the full extent of this location, as well as a multi-resolution depth model combining all available hydrographic data in the region.

This report consists of four primary components: 1) a description of the classification scheme used to categorize the different seafloor habitats; 2) a description of the techniques used to create the habitat maps; 3) an assessment of the habitat maps' thematic accuracies; and 4) a discussion and summary of the habitats in each area.

These habitat maps will be used by Puerto Rico's Department of Natural and Environmental Resources (DNER), the University of Puerto Rico (UPR), NOAA and other local partners for planning research and monitoring activities, and will support the management and conservation of the Northeast Reserves. This work is part of NOAA Coral Reef Conservation Program's national coral reef ecosystem integrated mapping and monitoring studies throughout the U.S. Caribbean. For more information on this effort please visit: <http://coastalscience.noaa.gov/projects/detail?key=258>

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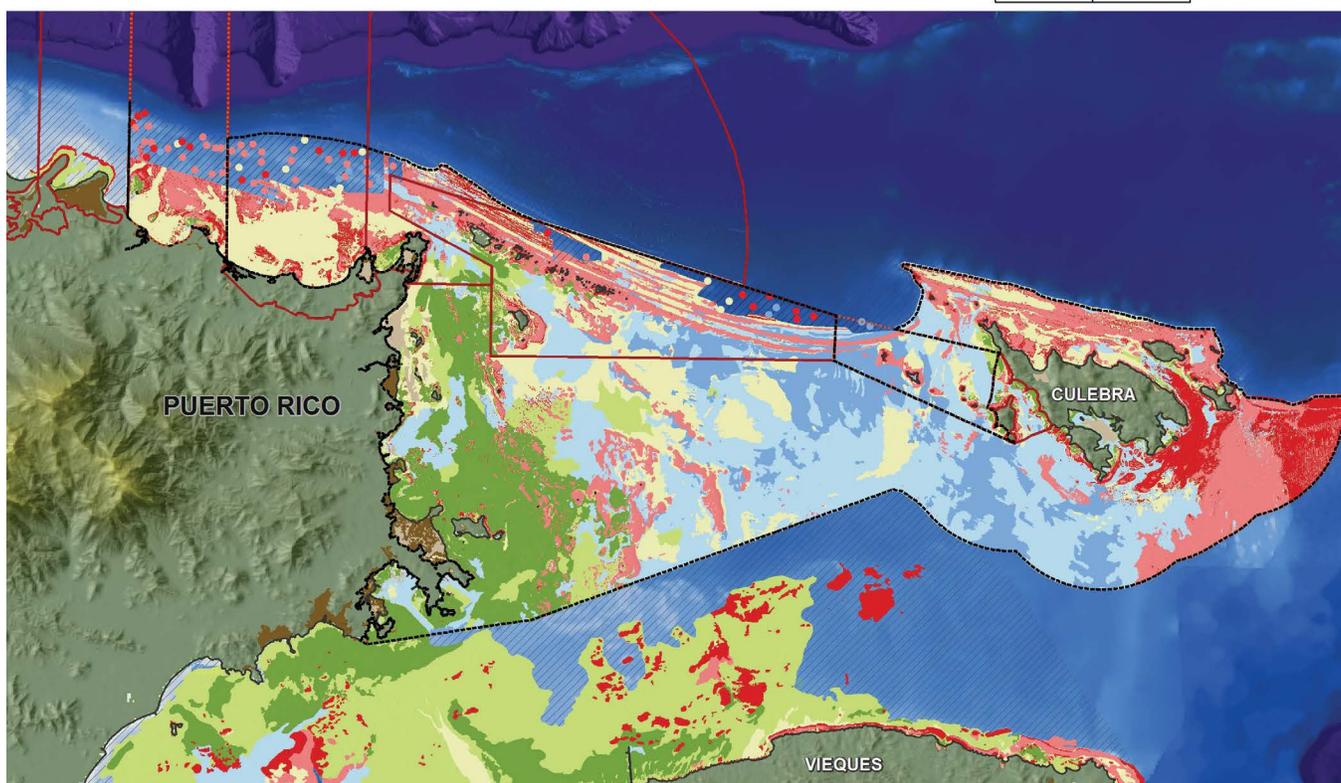
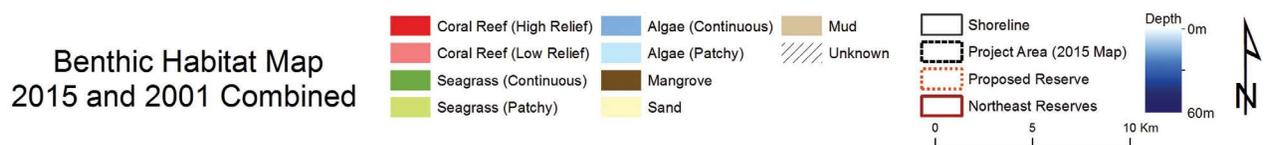
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EXECUTIVE SUMMARY

The Biogeography Branch of NOAA's National Centers for Coastal Ocean Science has mapped and characterized large portions of the coral reef ecosystems inside coastal and territorial waters of the United States, including the Caribbean. The protocols used in these efforts have enabled scientists and managers to quantitatively and qualitatively compare different marine ecosystems in tropical U.S. waters. The Biogeography Branch used similar protocols to generate new benthic habitat maps for Northeast Puerto Rico (NEPR) and Culebra Island, including shallow waters within the Northeast Reserves. While this endeavor marks the second time that these shallow-water habitats (<35 m) have been mapped, this product provides greater detail and spatial coverage. This project has also included the collection and processing of new remote sensing information that describes the seafloor in and around the mapping area, using both high resolution satellite imagery and a new, multi-resolution depth model. Consequently, this imagery and habitat map provides new information describing the distribution of coral reef ecosystems. These products serve as a spatial baseline for understanding current conditions and monitoring future changes in the region around NEPR and Culebra Island.

The benthic habitat map covered approximately 744 km² of seafloor in and around NEPR and Culebra and included 250 km of detailed shoreline along with 210 islands and smaller rock outcrops. Twenty-five percent (183 km²) of this habitat map describes the seafloor inside the boundaries of the Northeast Reserves, a series of marine reserves that stretches from Puerto Rico to Culebra Island. The remaining seventy-five percent (561 km²) of this habitat map describes the seafloor outside of the Reserves boundaries. The new map covers 545 km² of previously unmapped benthic habitats, and provides an update for an additional 170 km² of benthic habitats that were previously mapped (2001) at a lower spatial resolution. This habitat map was developed using a combination of semi-automated and manual classification methods. Habitats



The map shows an overview of the benthic habitats of NEPR and Culebra Island using both the old map from 2001 and the new map from 2015. A detailed description of the habitat overview definitions can be found in Chapter 2, Table 2.2 (pg. 31).

were interpreted based on aerial photographs, high resolution satellite imagery and a new depth model developed from recent hydrographic surveys (Lidar and Multibeam) and historical data. In total, 1,004 unique combinations of habitat classes describing the geology and biology of the seafloor were identified from the source imagery. In addition to the benthic habitat map, detailed habitat information was collected from 1,817 video transects across the region, including 461 sightings of Endangered Species Act (ESA) listed *Acropora* corals, faunal observations and water visibility data.

Unconsolidated sediments dominated these regions whereas hardbottom, including coral reefs, covered a quarter of the mapped area. Live coral cover varied across the region and exceeded 10 percent in half of the mapped hardbottom areas, but was rarely found covering more than 50 percent of the seafloor. A majority of the reefs with high relief and relatively high coral cover were located outside of existing marine protected areas east of Culebra Island, as were a majority of the areas covered by seagrass found between Puerto Rico and Vieques Island. A large hardbottom region with very low coral cover was identified along the northern coast of Puerto Rico. The overall map accuracies (corrected for proportional bias) were as follows: 90% for major and 64% for detailed geomorphological structure, 82% for percent hardbottom, 71% for topographic complexity, 83% for biological cover and 76% for live coral cover.

This report documents the process and methods used to create the shallow water benthic habitat maps for NEPR and Culebra. Chapter 1 provides a short introduction to the region, including the history of the Northeast Reserves, a review of marine life and threats to the coastal ecosystems, and a summary of why the area was selected as a priority site by local managers. Chapter 2 describes the benthic habitat classification scheme used to partition the different habitats into ecologically relevant groups. It also provides a key that translates this scheme to the Coastal and Marine Ecological Classification Standard (CMECS). Chapter 3 explains the steps required to create a benthic habitat map using a combination of semi-automated and visual classification techniques. Chapter 4 details the steps used to assess map accuracy and reports the thematic accuracy of the final shallow-water map. Chapter 5 summarizes the type and abundance of each habitat class, and how these habitats compare to past habitat maps. It also outlines how these new habitat maps may be used to inform future management activities. The final deliverables for this project are available to the public: (1) on the web (<http://coastalscience.noaa.gov/projects/detail?key=258>) and (2) through an interactive, web-based map application (<http://maps.coastalscience.noaa.gov/biomapper/biomapper.html?id=prne>).

CHAPTER 1: INTRODUCTION

This report describes the mapping of 744 km² of shallow-water (<35 m) benthic habitats in northeast Puerto Rico (NEPR) and Culebra Island (Figure 1.1) conducted by NOAA. The area mapped includes four marine reserves and borders one reserve (hereafter referred to as the Northeast Reserves). The extent and location of this habitat mapping effort was chosen as a result of close consultation between NOAA's Coral Reef Conservation Program (CRCP), NOAA's National Centers for Coastal Ocean Science (NCCOS) Biogeography Branch and the Department of Natural and Environmental Resources of Puerto Rico (DNER). NEPR and Culebra were recently designated as a NOAA Habitat Blueprint Area (January 2015), which means that additional resources will be made available to help the Government of Puerto Rico to protect, restore and manage the regions rich and valuable marine ecosystems in the future. The habitat maps presented in this report were developed to support these ongoing efforts by providing essential coral reef ecosystem information. A NOAA project called *Spatial Characterization of the Northeast Reserves* is incorporating the new habitat data as part of an effort to identify areas of ecological importance and assess the threats to those resources.

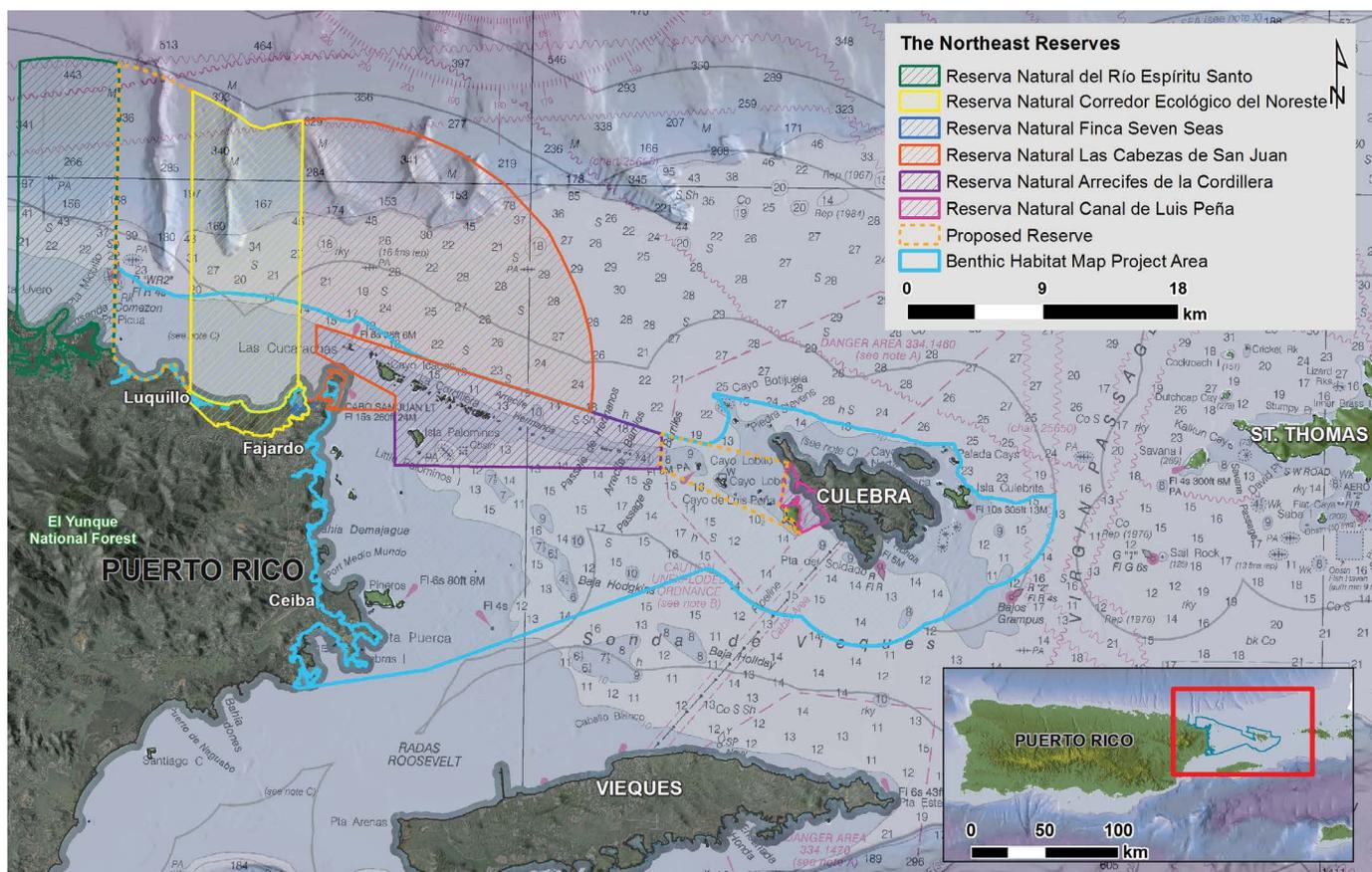


Figure 1.1. The mapped area includes four natural reserves extending from Puerto Rico across the Vieques Strait to Culebra Island (here referred to as the Northeast Reserves) as well as a large swath of unmanaged coral reef ecosystems south of the Northeast Reserves and around Culebra. The northern extent of the mapping boundary is limited to depths shallower than 35 meters, while the southern extent is derived from a three nautical mile shoreline buffer to limit the scope of work. The extent of the Northeast Reserves is under evaluation and may change (see proposed reserve boundary), however this report refers to the current boundaries as of April 2015.

1.1. DEVELOPING A NEW HABITAT MAP

The new fine-scale habitat map provides spatially-explicit information on habitat types, biological cover, and live coral cover extending over a large and biologically complex area. To address this challenge, NOAA developed a semi-automated habitat mapping approach which compensates for varying localized conditions. The waters around NEPR are often turbid, which limits aerial photo and satellite collections. Although hydrographic data was available in the project area, its spatial resolution varied from regions with high resolution multibeam sonar and Lidar data, to areas with very sparse data coverage (some areas had not been

mapped since the early lead line surveys conducted in the beginning of the 20th century). To meet these challenges, a new multi-resolution depth model was developed for the region using geostatistical modeling that incorporated all the available data, as well as a high resolution seafloor mosaic (i.e. Worldview-2 satellite data collected from 2011-2013). The UPR and the Caribbean Coastal Ocean Observation System (CariCOOS) contributed by developing a new high resolution oceanographic model of the area with wave height and current data.

The methods and findings presented in this report combine previously established protocols with novel habitat mapping and geospatial modeling approaches. Many of the tools and techniques developed for this project will have mapping applications in other temperate and tropical locales, and are especially relevant to regions where large patchy and heterogeneous habitat distributions exist. The new habitat map is a regional update to NOAA's previous digital maps of the U.S. Caribbean (Kendall, et al., 2001) with improved coverage and higher spatial and thematic resolutions.

In addition to developing the habitat map, underwater videos were collected and used to identify ESA-listed (Endangered Species Act) coral locations and fauna sightings, including turtles, large reef fish (groupers, sharks, rays), lobsters and invasive species (lionfish). An inventory of water visibility was also produced to discern areas where turbid water was present or prevalent. Reliable data for water visibility has been identified as one of the main gaps in information critical to understanding threats to coral reefs in the Caribbean (Jackson, et al., 2014). These underwater observations provided additional value-added characterization of the region and will be used to help DNER prioritize areas around NE Puerto Rico for zoning and other management actions.

The products generated by this project in and around the Northeast Reserves and Culebra Island include:

- Benthic habitat map
- Geographic zone map
- Classification manual (this report)
- Bathymetry model (i.e., depth imagery)
- High resolution satellite imagery seafloor mosaic
- Underwater videos and photos (geo-located)
- Detailed habitat information derived from videos and photos
- Water visibility information derived from videos and photos
- ESA coral sighting, and fauna observations derived from videos and photos

1.2. DESCRIPTION OF THE MAPPING AREA

Puerto Rico is located on the geological feature known as the Puerto Rican Bank, which includes the U.S. Virgin Islands (USVI) and the British Virgin Islands on the eastern end of the Greater Antilles (Figure 1). The U.S. Territories of PR and USVI together form the U.S. Caribbean exclusive economic zone (EEZ), which includes their surrounding waters out to 200 nautical miles. Puerto Rico is the fourth largest Caribbean island (9,000 km²) populated by 3.7 million people, as well as a number of smaller islands, the largest of which are Vieques (population 9,301), Culebra (population 1,818) and Mona Island (no permanent inhabitants) (Census, 2012).

NEPR and Culebra are home to many different terrestrial and marine habitats ranging from the tropical rainforest in the mountains (El Yunque National Forest) to rich coastal areas with forests and wetlands, a bioluminescent lagoon, isolated beaches, coral reefs, extensive seagrass beds and a patchwork of small cays. Caribbean reef habitats provide sources of food and refuge for a diversity of juvenile and adult organisms, as well as valuable ecosystem services to the local community, including shoreline protection, fisheries replenishment, recreation, and tourism (Waddell and Clarke, 2008). Many marine species listed as threatened or endangered are present in the area, including corals, fish, turtles, manatees, seabirds and whales (García-Sais, et al., 2008)

The ecosystems contained within and surrounding NEPR and Culebra support a substantial tourism economy, but are under increasing pressure from many stressors, as are a majority of the coral reef habitats

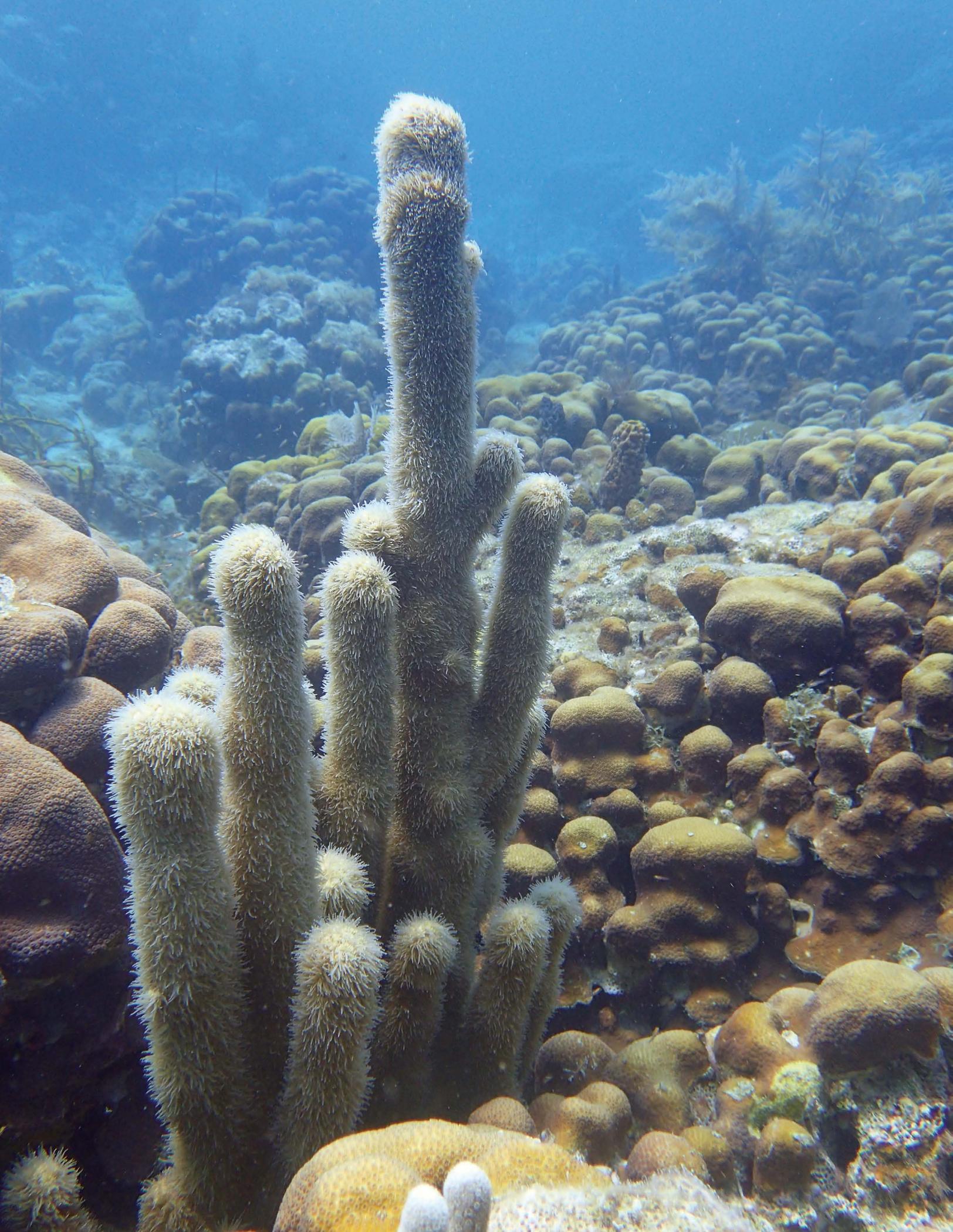
around the Caribbean. The combination of coastal development, agriculture and fishing are the largest contributors to the massive decline in richness and biodiversity of coral reef ecosystems in the Caribbean that has occurred since the middle of the 20th century (Jackson, et al., 2014). The coastal waters in NEPR receive a large influx of sediment, pollutants and nutrients from eroding land and developed coastal areas, and are also subject to wave induced re-suspension of seafloor sediment deposits. This has led to deteriorating water quality and conditions conducive to coral ecosystem health (Warne, et al., 2005). The waters around Culebra are similarly affected by runoff, but to a lesser extent due to the island's geography and smaller population (Census, 2012; Warne, et al., 2005). Other stressors in the region include recreational and commercial fishing, maritime vessel traffic, tourism, invasive species, pathogens (diseases), unexploded military ordnance from past U.S. military presence, and rising water temperatures. Even though the marine and coastal habitats have been severely impacted by multiple stressors, there are still large areas with rich coral reef habitats, as shown in this report. Currently, there are existing and planned marine conservation efforts to identify and increase protection of sensitive areas, and to restore lost reef habitats being carried out by nonprofit organizations, local communities, and stakeholders, as well as DNER and NOAA.

1.3. THE NORTHEAST RESERVES

The establishment of marine reserves within the mapping area began in 1975 when the Conservation Trust of Puerto Rico acquired the land area of the Cabezas de San Juan to conserve its bioluminescent lagoon and historic Spanish lighthouse. The Reserve was later extended out to nine nautical miles in order to protect the surrounding marine habitats. In 1980, the Puerto Rico Planning Board created the Arrecifes de la Cordillera Nature Reserve. In 1991, the board developed a management plan to protect this chain of cays which extend seaward from the Cabezas de San Juan Natural Reserve across the Vieques Sound (E. Alecia, personal communication, May 2015).

Culebra Island was recognized by natural resource managers as an area of high ecological value that should be protected. In 1999, the Canal Luis Peña Natural Reserve (CLPNR) was created by the Puerto Rico Coastal Zone Management Program. The designation effort was catalyzed by the Culebra Fisher's Association, community members, local groups, and the scientific community. A management plan was developed and approved through NOAA's National Fish and Wildlife Foundation partnership grant funds with stakeholder input and a no fishing zone within the CLPNR was implemented in September 2008 (E. Alecia, personal communication, May 2015).

The latest edition of nature reserves is the Reserva Natural Corredor Ecologico del Noreste between Luquillo and Fajardo, which was proposed by a grassroots movement in the late 1990s. It was signed into law in 2013 and extended the boundaries of the Cabezas de San Juan Natural Reserve to the nine nautical mile Territorial Sea boundary. A new management plan is currently being developed for the area (E. Alecia, personal communication, May 2015). Additionally, legislation is currently being proposed by the Puerto Rico Planning Board to develop a new marine management area that could connect all the reserves to form a marine ecological natural corridor between Northeast Puerto Rico and Culebra Island (E. Alecia, personal communication, May 2015). The full extent of the Northeast Reserves may therefore change in the near future. This report refers to the current boundaries as of April 2015 (Figure 1.1).



CHAPTER 2: BENTHIC HABITAT CLASSIFICATION SCHEME

A habitat classification scheme allows scientists to systematically group habitat types based on common ecological and geomorphological characteristics. The initial task in any mapping effort is to develop a classification scheme by clearly identifying and defining discrete habitat classes. The scheme is used to guide the delineation and attribution of polygons during the mapping process. It is essential for map users to have an understanding of the classification system, its structure and its definitions. This understanding allows users to decide on the appropriate applications and limitations of the habitat map.



Figure 2.1. Culebra Island's complex geomorphology creates a mix of many different geographic zones. This photograph shows the transition from the dark blue waters of the bank/shelf zone in the background to the emergent reef crest that protects the shallow reef flats, seagrass beds, and mangroves of the lagoon.

The classification scheme used to map the coral habitats in Northeast Puerto Rico and Culebra Island (Figure 2.1) identifies benthic communities based on five primary coral reef ecosystem attributes: (1) geographic zone; (2) geomorphological structure; (3) percent hardbottom; (4) major biological cover; (5) live coral cover. We also mapped two additional attributes, topographic complexity and dominant coral cover (hard/soft/mixed corals). Habitat features are described by varying levels of detail (i.e., major and minor categories nested within them), so users can depict the habitat information that best suits their research or management needs.

The thematic resolution in the scheme varies for each habitat class category, from three unique attributes for *percent biological cover* to 15 unique habitat attributes in *detailed geomorphological structure*, see Table 2.1 for a complete overview. The combined habitat classification scheme has a high number of possible unique combinations which points to some of the challenges with habitat mapping in high thematic resolution, especially for hardbottom areas.

2.1. DEVELOPING THE CLASSIFICATION SCHEME

Many important factors were considered when developing the habitat classification scheme. These factors included: (1) how it would coincide with existing classification schemes for marine habitats; (2) what limitations were associated with the source imagery; (3) how to best create a habitat map from multiple imagery sources with different spatial resolutions and quality; (4) what would be an appropriate minimum mapping unit (MMU); and (5) how much ground validation (i.e., underwater video) would be needed to create a habitat map.

To simplify this process, we based the habitat classification on the scheme previously used by NOAA to map benthic habitats around the St. Thomas East End Reserve (Costa et al. 2013) and in Buck Island Reef National Monument north of St. Croix in the U.S. Virgin Islands (Costa et al. 2012). Generally speaking, the geographic zones, major and detailed geomorphological structures and biological cover types were the same across these habitat maps. Two experimental modifier categories were added to the habitat map based on the underwater video analysis, *Topographic Complexity* and *Dominant Coral Cover* (hard/soft/mixed corals).

In addition to the two new experimental modifier classes that were included in the map, other ecologically important information was extracted from the underwater videos. This included information about visibility,

Table 2.1. The classification scheme used to classify benthic habitats in the Northeast Reserve, Puerto Rico in 2014. The classification scheme was modeled after the one used by Costa, et al., 2013 for the St. Thomas East End Reserve. Classes with a line crossed through them were not present in the NER, but were included for comparison purposes.

Geographic Zone	Geomorphological Structure		Biological Cover	
Back Reef	Coral Reef and Hardbottom (Hard)	Percent Hard	Major Cover	
Bank/Shelf	Aggregate Reef		0% ≤ 10%	Algae
Bank/Shelf Escarpment	Aggregated Patch Reefs		10% ≤ 30%	Live Coral
Channel	Individual Patch Reef		30% ≤ 50%	Mangrove
Dredged	Pavement		50% ≤ 70%	No Cover
Fore Reef	Pavement with Sand Channels		70% ≤ 90%	Seagrass
Lagoon	Reef Rubble		90% - 100%	Unclassified
Land	Rhodoliths		N/A	Unknown
Reef Crest	Rhodoliths with Scattered Coral & Rock		Unknown	Percent Major Cover
Reef Flat	Rock/Boulder			10% ≤ 50%
Reef Ridge Complex*	Spur & Groove	Topographic Complexity**	50% ≤ 90%	
Salt Pond	Unconsolidated Sediment (Soft)		Very Low	90% ≤ 100%
Shoreline Intertidal	Mud		Low	N/A
	Sand		Moderate	Unknown
	Sand with Scattered Coral & Rock		High	Percent Coral Cover
	Other Delineations		Very High	0% ≤ 10%
	Artificial			10% ≤ 50%
	Land			50% ≤ 90%
	Unknown			90% ≤ 100%
				N/A
			Unknown	

*New Zone; **Experimental class

biological cover, presence of Endangered Species Act listed *Acropora* species, and information about fauna observed. The additional habitat information is presented as point data only, but could potentially be used to create predictive models of species distributions in the area.

Although the map created for Northeast Puerto Rico and Culebra Island is similar to the previous maps in the region, it is fundamentally different from the benthic habitat map created in 2001 by NOAA's Biogeography Branch for Puerto Rico and USVI (Kendall, et al., 2001). The primary differences between NOAA's 2001 and 2014 habitat maps include: (1) the separation of biological cover from habitat structure; (2) a much finer MMU size (i.e., 4,047 m² versus 100 m²); (3) the addition of more detailed structure classes as a result of the higher resolution of the source imagery and smaller geographic scope of the map project; and (4) the addition of four new map attributes (*percent hardbottom*, *topographic complexity*, *percent live coral cover*, and *dominant coral type*). The new map also covers large areas that were previously classified as *Unknown* due to limited data available at the time.

Coastal and Marine Ecological Classification Standard (CMECS)

The classification scheme used by NOAA's Biogeography Branch for this mapping effort has been translated to the US Coastal and Marine Ecological Classification Standard. A full cross walk between the implemented habitat scheme and CMECS is found in Table 2.3 (pg.32). CMECS provides a comprehensive national framework for organizing information about coasts and oceans and their living systems. This information includes the physical, biological and chemical data that are collectively used to define coastal and marine ecosystems (FGDC, 2012). The intention of the CMECS translation table is to make it easier to compare and analyze the developed habitat map with habitat data from other groups and regions, while preserving the habitat scheme used by NOAA's Biogeography Branch to map nearby areas in the U.S. Caribbean. In addition to the crosswalk, CMECS also provided the Biogeography Branch with language and guidelines to enhance the pre-existing benthic habitat scheme. The addition of new categories (*Topographic Complexity*, *Visibility* and *Co-occurring Biological Cover*) and a new Geographic Zone (*Reef Ridge Complex*) to the Biogeography Classification Scheme was in part based on CMECS. Modifications were made to adjust to the available data in the mapping area, so the final attributes differ some from their CMECS equivalent.

2.2 GEOGRAPHIC ZONES

Twelve distinct geographic zone types were mapped by visually interpreting the bathymetry model, aerial photos, and satellite imagery together with the classified habitat map. A zone refers to each benthic community's geographic location and geomorphology. It does not describe a polygon's substrate or biological cover types. For example, the zone *Reef Crest* is always located adjacent to a *Fore Reef* on the landward side. Additionally, the location of particular zone types may change depending on whether the system is a barrier reef, fringing reef or when no emergent reef crest is present (Figures 2.2 - 2.5). Habitats or features with areas smaller than the MMU (100 m²) were not considered. A description of each geographic zone is provided in the following text.

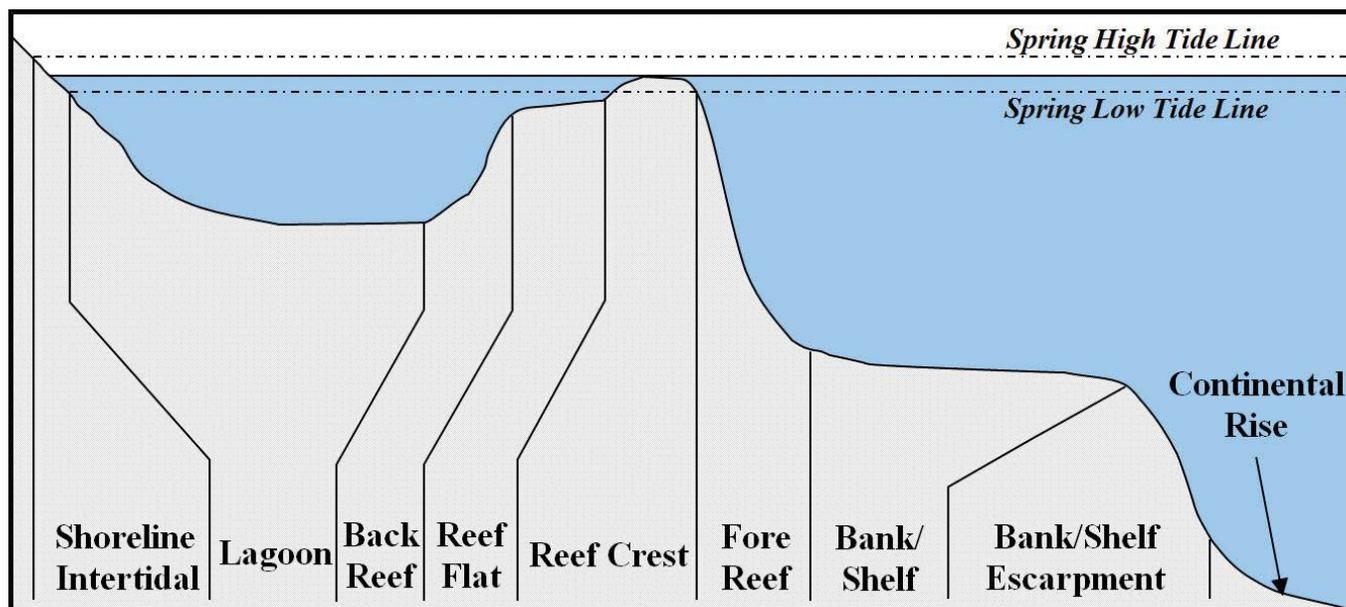


Figure 2.2. Cross-section of zone types when a barrier reef is present. The reef is separated from the shore by a relatively wide and deep lagoon.

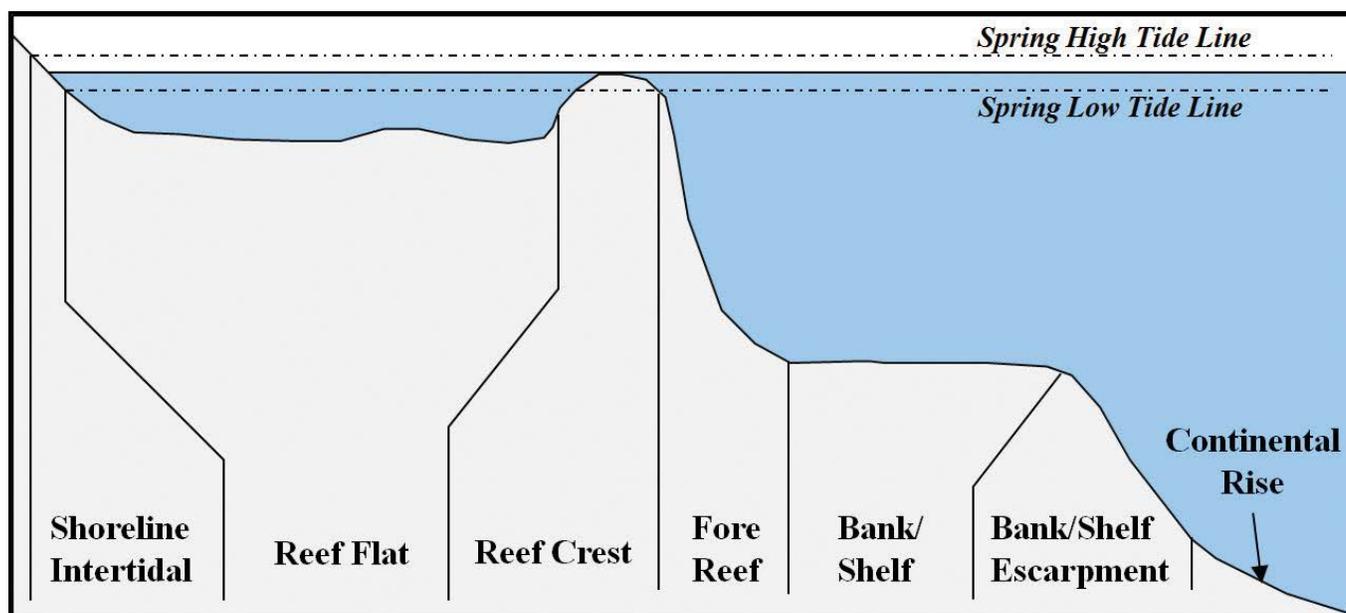


Figure 2.3 Cross-section of zone types when a fringing reef is present. The reef platform is continuous with the shore.

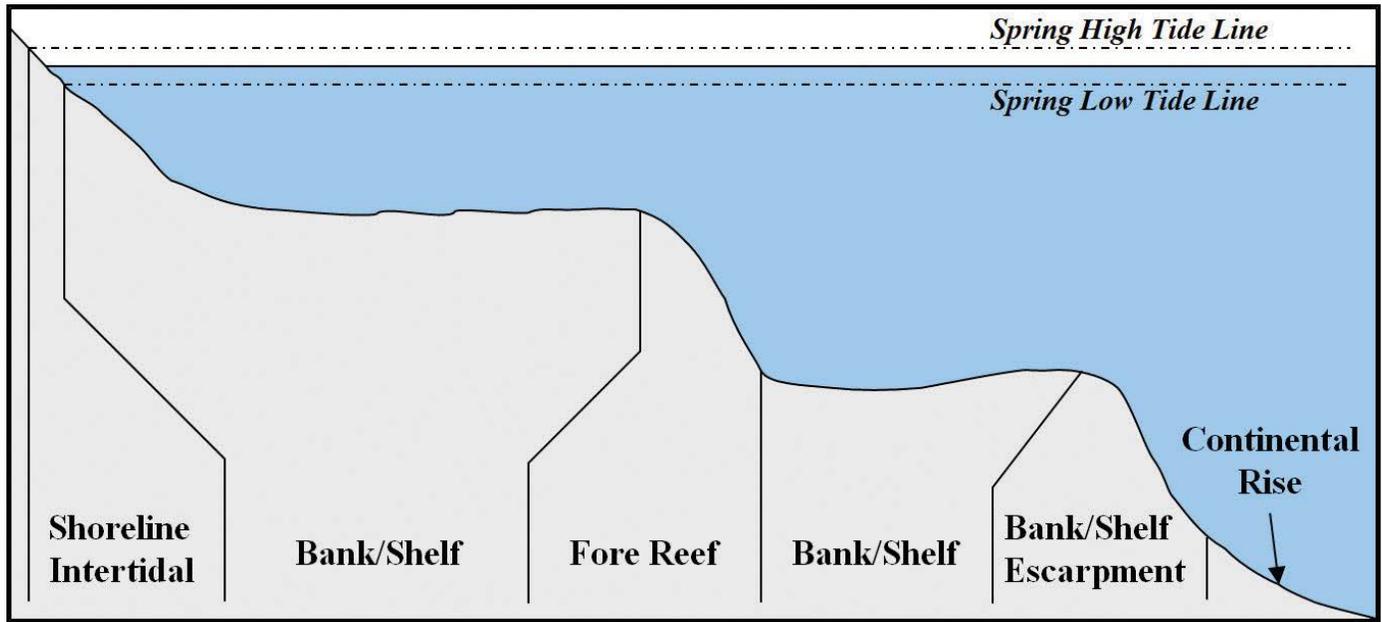


Figure 2.4. Cross-section of zone types when no emergent reef crest is present.

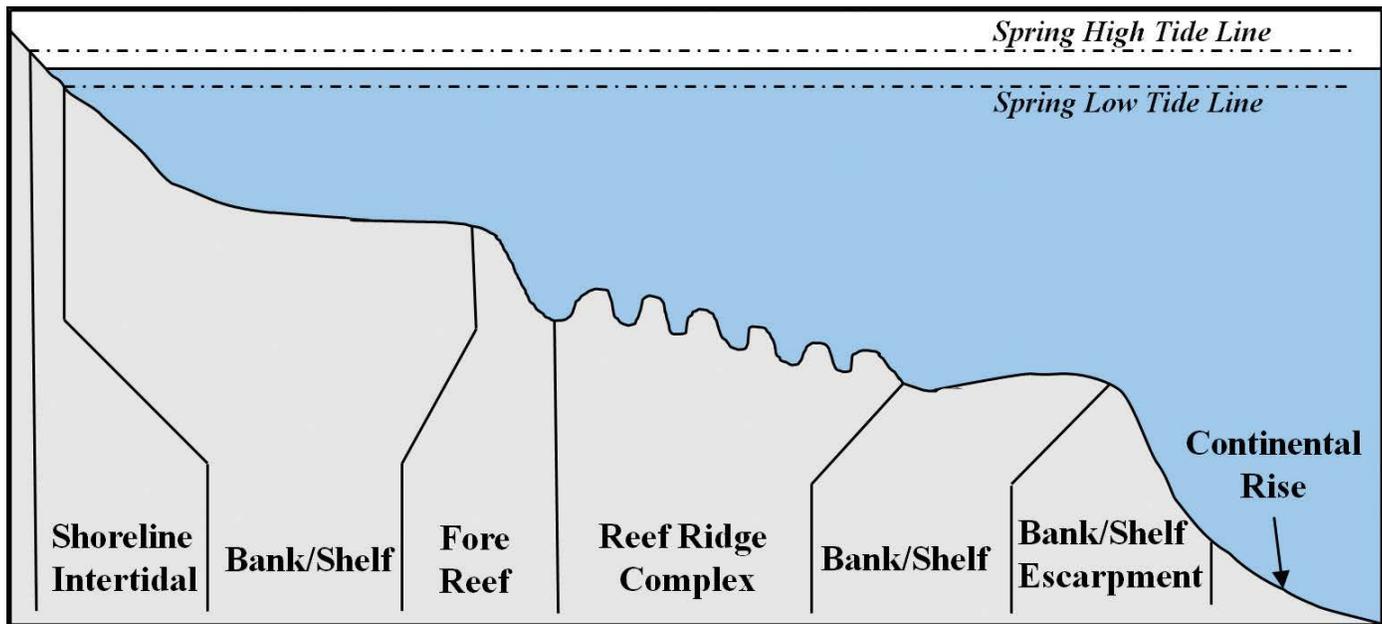


Figure 2.5. Cross-section of zone types when a reef ridge complex is present.

Land

Terrestrial features at or above the spring high tide line. Shoreline delineations describing the boundary between land and submerged zones are established at the wrack line where possible or the wet line at the time of imagery acquisition (Figure 2.6). The wrack line is a line of organic and/or anthropogenic debris (above the mean high tide line) that has been deposited by previous tides.



Figure 2.6. The red polygons on the satellite imagery outline examples of the geographic zone, *Land*. On the left is an image of the densely populated coastal city of Fajardo. On the right are the uninhabited cays of the Luis Pena Reserve.

Shoreline Intertidal

Broadly defined as the area between the spring highest high and lowest low tide levels. Typically, this area is narrow due to the small tidal range in the U.S. Caribbean. The *Shoreline Intertidal* zone, as defined in this habitat scheme, also includes intertidal and subtidal mangrove habitats up to the landward edge. Emergent segments of barrier reefs are excluded from this zone (Figure 2.7).

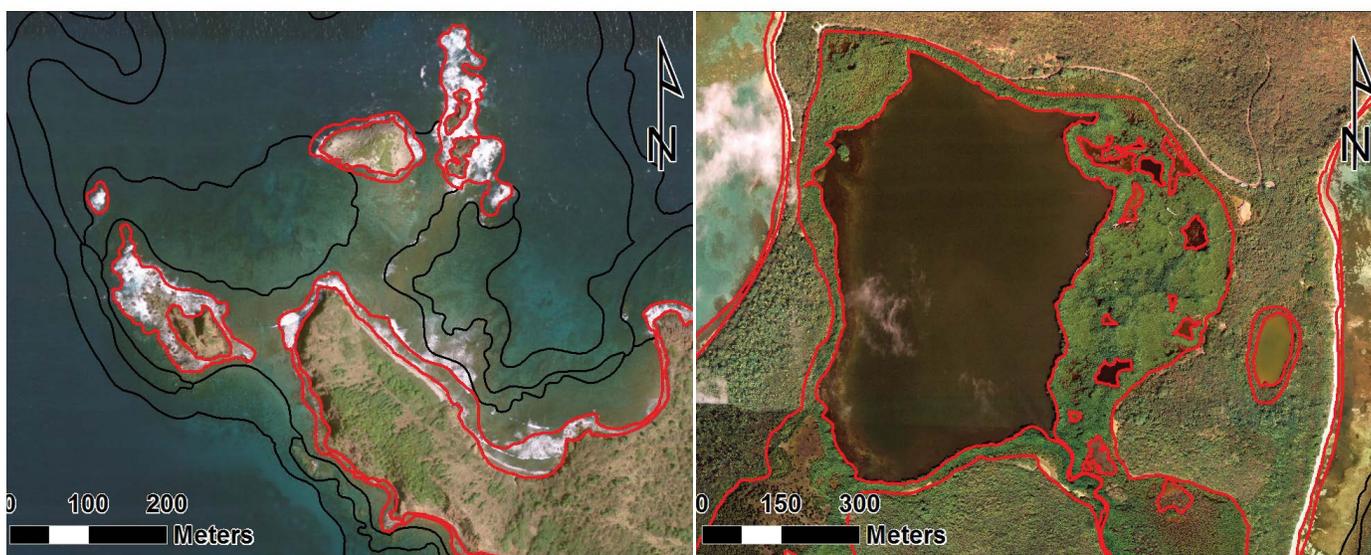


Figure 2.7. The satellite image on the left shows an example of the geographic zone, *Shoreline/Intertidal*, outlined in red, on the northwest point of Culebra Island. The image on the right shows a mangrove *shoreline/intertidal* zone surrounding the large inland lagoon of the Cabeza de San Juan.

Channel

Naturally occurring channels that often cut across several other zones. This also includes stream channels that may cut across mangroves or lowland intertidal zones to a lagoon or the sea (Figure 2.8).



Figure 2.8. The red polygons on the satellite imagery outline examples of the geographic zone, *Channel*. On the left is an example of a channel that cuts through a fringing reef into a lagoon. On the right is an example of two channels that cut through a mangrove intertidal zone to the sea.

Dredged

Area in which natural geomorphology is disrupted or altered by excavation or dredging. This zone includes the area of the seafloor that has been scoured out and where the dredged sediment has been deposited (Figure 2.9).

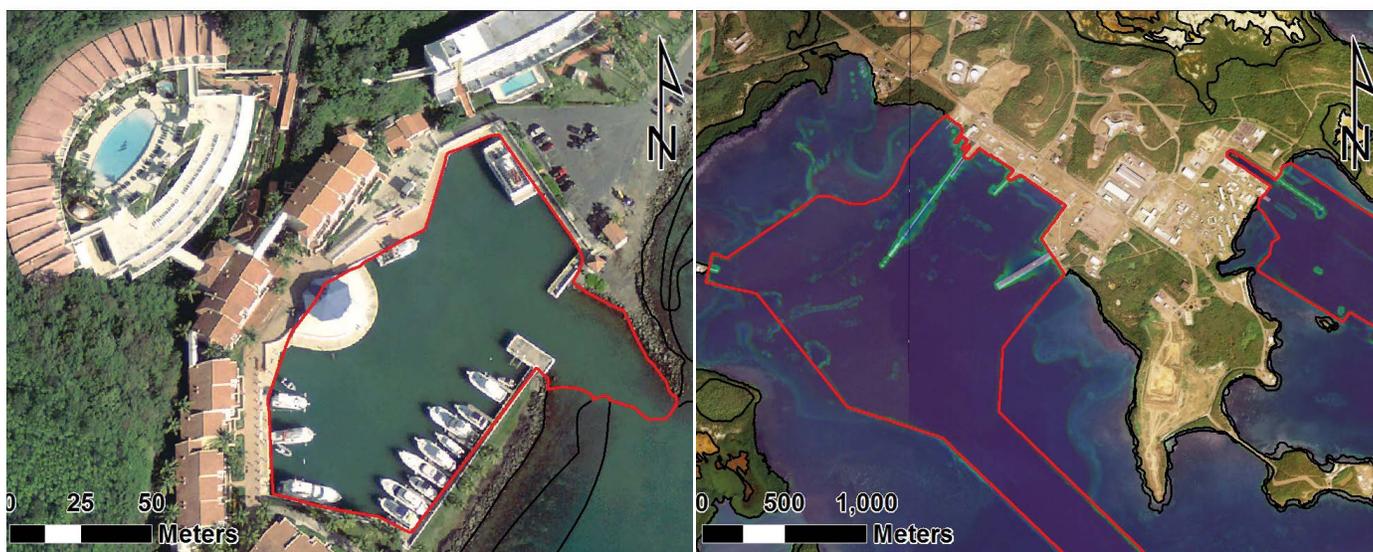


Figure 2.9. The red polygons on the satellite imagery outline examples of the geographic zone, *Dredged*. On the left is the dredged private marina of the Conquistador Resort in Fajardo. On the right is the former Roosevelt Roads Naval Station near Ceiba that has had extensive dredging to allow passage of large ships.

Salt Pond

Enclosed area immediately landward of the shoreline with a permanent or intermittent flooding regime of saline to hypersaline waters (Figure 2.10).



Figure 2.10. The satellite image on the left shows an example of the geographic zone, *Salt Pond*, outlined in red. On the right is a photograph of an enclosed salt pond near the north coast of Culebra Island.

Lagoon

Shallow area (relative to the deeper water of the *Bank/Shelf*) between the *Shoreline Intertidal* zone and the *Back Reef* of a reef or a barrier island. This zone is typically protected from the high-energy waves commonly experienced on the *Fore Reef* and *Reef Crest* zones (Figure 2.11).

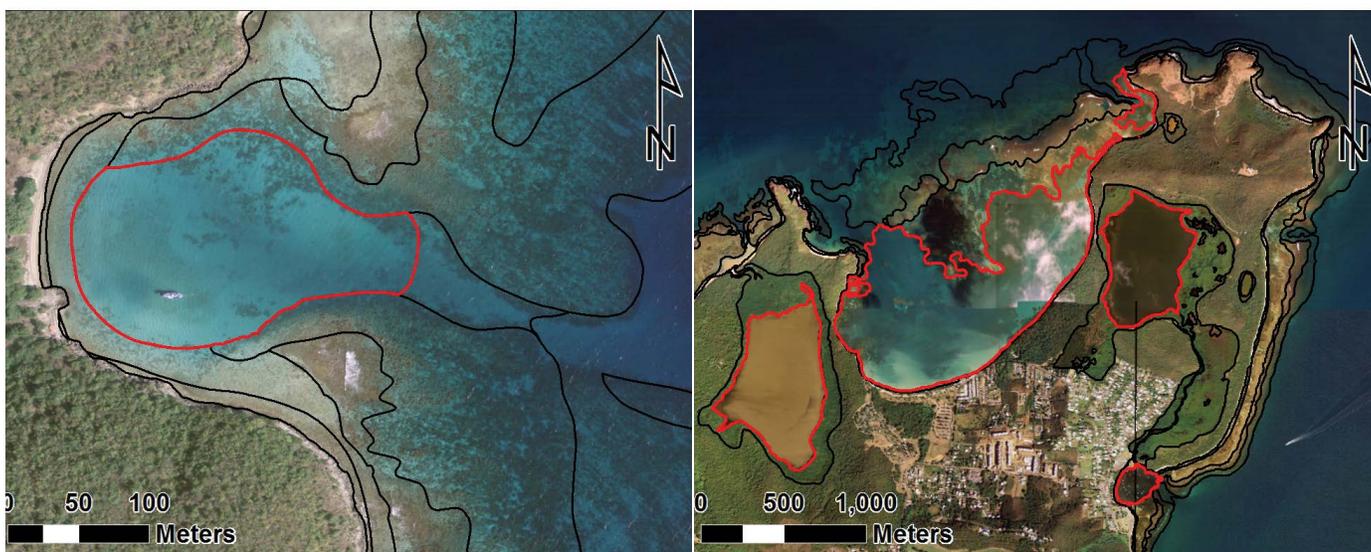


Figure 2.11. The red polygons on the satellite imagery outline examples of the geographic zone, *Lagoon*. *Lagoons* can appear in shallow bays protected by reefs, as seen in Cayo Luis Pena (left), and can also appear inland, surrounded by mangroves and connected by small channels to the sea, as seen at Cabeza de San Juan (right).

Back Reef

Area immediately landward of a *Reef Crest* that slopes downward towards the seaward edge of a *Lagoon* floor or *Bank/Shelf*. This zone is present only when a *Reef Crest* exists (Figure 2.12).

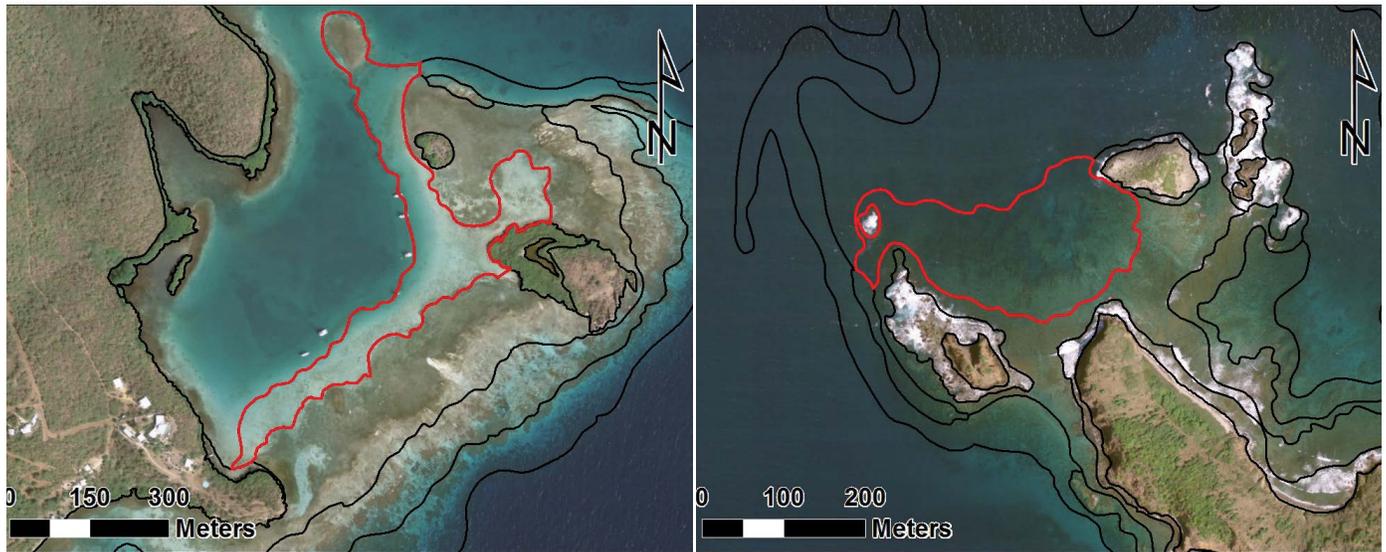


Figure 2.12. The red polygons on the satellite imagery outline examples of the geographic zone, *Back Reef*. On the left is a *Back Reef* that transitions into a *Lagoon* in Culebrita Island, and on the right is a *Back Reef* that transitions into a *Bank/Shelf* zone off of Culebrita Island.

Reef Flat

The shallow, semi-exposed area with little relief between the *Shoreline Intertidal* zone and the *Reef Crest* of a fringing reef. This broad, flat area often exists immediately landward of a *Reef Crest* and may extend to the shoreline or drop into a *Lagoon*. This zone is protected from the high-energy waves commonly experienced on the *Bank/Shelf* and *Reef Crest* zones (Figure 2.13).

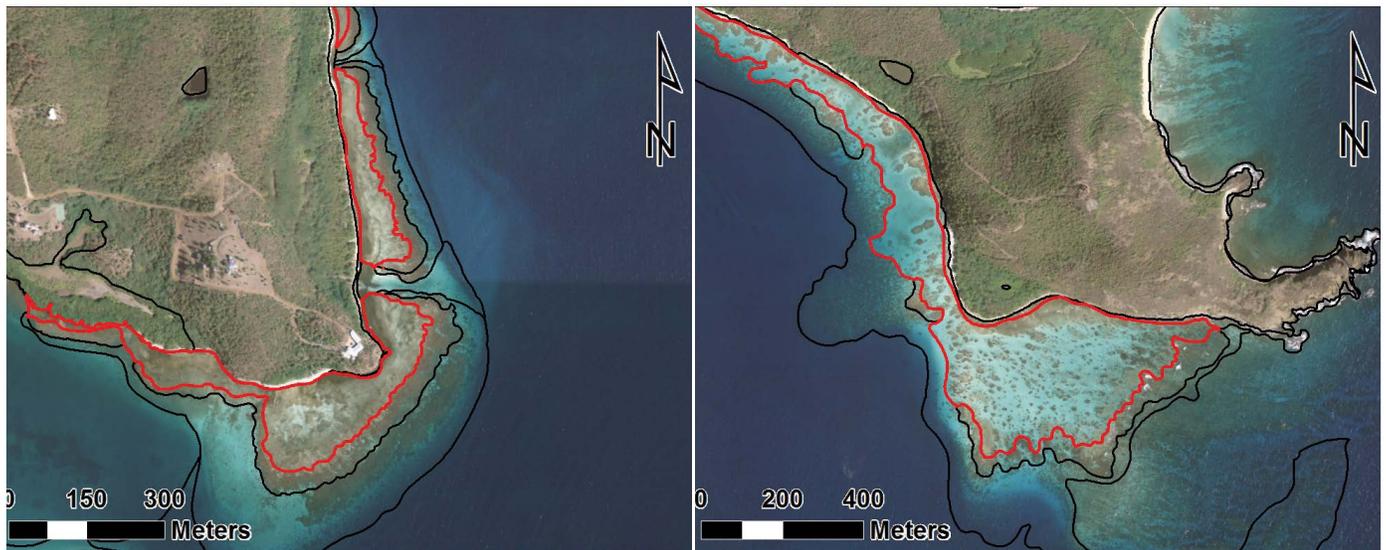


Figure 2.13. The red polygons on the satellite imagery outline examples of the geographic zone, *Reef Flat*. On the left is a reef flat on Culebrita Island that does not have a continuous reef crest. On the right is an example of a reef flat in Culebrita island that is protected by a reef crest that has been cut by small channels.

Reef Crest

The often linear, flattened, and emergent (especially during low tides) or nearly emergent segment of a reef. This zone of high wave energy lies between the *Fore Reef* and *Back Reef* or *Reef Flat* zones. Breaking waves are often visible in overhead imagery at the seaward edge of this zone (Figure 2.14).



Figure 2.14. The red polygons on the satellite imagery outline examples of the geographic zone, *Reef Crest*. On the left is a classic reef crest that transitions into a reef flat on the south side of Culebra. On the right is an example of a reef crest that transitions into a deep *Back Reef* off of Culebrita Island.

Fore Reef

Area along the seaward edge of the *Reef Crest* that slopes into deeper water to the landward edge of the *Bank/Shelf* platform. Features not associated with an emergent *Reef Crest* (but still having a seaward-facing slope that is significantly greater than the slope of the *Bank/Shelf*) are also designated as *Fore Reef* (Figure 2.15).

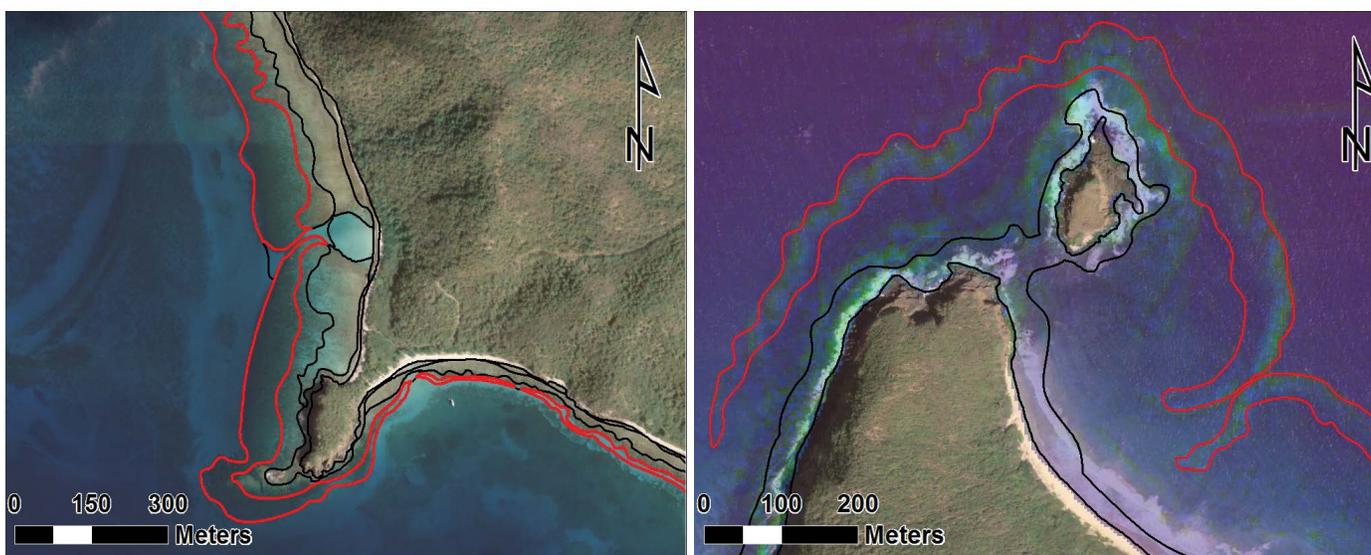


Figure 2.15. The red polygons on the satellite imagery outline examples of the geographic zone, *Fore Reef*. On the left is a classic fore reef in Culebra that transitions from the bank/shelf up to a reef crest. On the right is a PCA image of a fore reef with no reef crest, but instead lies between a *Bank/Shelf* zone along the north coast of Culebra.

Bank/Shelf

Deeper water area (relative to the shallow water in a lagoon) extending offshore from the shoreline or seaward edge of the *Fore Reef* to the beginning of the *Bank/Shelf Escarpment*. If no *Reef Crest* is present, the *Bank/Shelf* is the flattened platform between the *Fore Reef* and deep open ocean waters or between the *Shoreline Intertidal* zone and open ocean (Figure 2.16).



Figure 2.16. The red polygons on the satellite imagery outline examples of the geographic zone, *Bank/Shelf*. On the left is a shallow lagoon and barrier reef system that drops into the deeper banks south of Culebra. On the right is a PCA image of a *Bank/Shelf* that is divided by a *Fore Reef* off the north side of the Cabeza de San Juan.

Reef Ridge Complex

An offshore area of numerous linear and discontinuous hard-bottom ridges followed by leeward troughs of unconsolidated sediments. This zone was created from relict shoreline/intertidal zones when sea level was lower than present day (Banks, et al., 2008). The ridges are generally flat-topped structures covered with soft corals and lack reef-building stoney corals. This zone is unique to the NEPR region among the U.S. Caribbean Territories (Kaye, 1959) but is similar to reef tracts along Southeastern Florida as described by Banks, et al., 2008 (Figure 2.17).

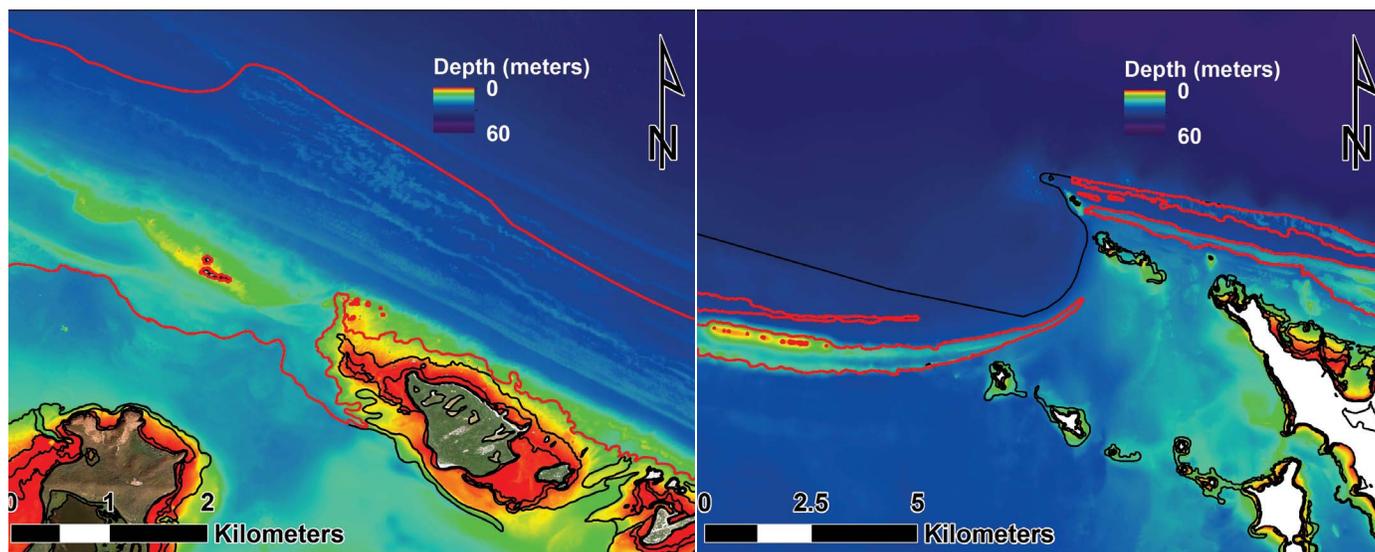


Figure 2.17. The red polygons on the bathymetry model outline examples of the geographic zone, *Reef Ridge Complex*. The image on the left shows the series of ridges and troughs offshore of La Cordillera. The image on the right shows the ridge reef complex extending from Puerto Rico across the Vieques Sound to Culebra Island.

2.3. GEOMORPHOLOGICAL STRUCTURE TYPES

Geomorphological structure refers to a feature's dominant physical composition and does not address its geographic location (e.g., in a *Lagoon*). Structure types are hierarchically defined ranging from three major classes (*Coral Reef and Hardbottom*, *Unconsolidated Sediment*, and *Other Delineations*), to thirteen detailed classes (*Aggregate Reef*, *Aggregated Patch Reefs*, *Individual Patch Reef*, *Pavement*, *Pavement with Sand Channels*, *Reef Rubble*, *Rhodoliths*, *Rhodoliths with Scattered Coral and Rock*, *Rock/Boulder*, *Spur and Groove*, *Mud*, *Sand*, *Sand with Scattered Coral and Rock*, *Artificial*, *Land* and *Unknown*).

Coral Reef and Hardbottom

Coral reef and Hardbottom habitats are areas on the seafloor with solid substrates, including bedrock, boulders and/or the deposition of calcium carbonate by reef building organisms. Substrates typically have no sediment cover, but a thin veneer of sand or mud may be present at times. Detailed structure classes include *Aggregate Reef*, *Aggregated Patch Reefs*, *Individual Patch Reef*, *Pavement*, *Pavement with Sand Channels*, *Reef Rubble*, *Rock/Boulder* and *Spur and Groove*.

Aggregate Reef

Continuous, moderate to high-relief coral formations of variable shapes, lacking the channels of *Spur and Groove*. Includes linear coral formations that are oriented parallel to the shelf edge. Relict reefs where little or no hard coral structures remain will be classified as *Pavement* (Figure 2.18).



Figure 2.18. The red polygons outline an example of the detailed structure type, *Aggregate Reef*, as seen in the enhanced satellite imagery of the northeast coast of Culebra (left). The underwater photography depicts an example of a healthy *Aggregate Reef* (middle), and a heavily degraded *Aggregate Reef* (right).

Aggregated Patch Reefs

Aggregated Patch Reefs have the same defining characteristics as an *Individual Patch Reef*. However, this class refers to clustered patch reefs that cover $\geq 10\%$ of the entire polygon, but are too small (i.e., smaller than the MMU, 100 m²) or too close together to map individually. Where aggregated patch reefs share sand halos, the halo is included in the polygon (Figure 2.19). If the density of small or aggregated coral heads is $< 10\%$ of the entire polygon, this structure type is described as *Sand with Scattered Coral and Rock*.



Figure 2.19. The red polygons outline an example of the detailed structure type, *Aggregated Patch Reefs*, as seen in the enhanced satellite imagery of the reef flat south of Culebrita Island (left). The underwater photography depicts an *Aggregated Patch Reef* from a shallow snorkel view (middle) to a deeper drop-camera view (right).

Individual Patch Reef

Coral formations that are isolated from other coral reef formations by bare sand, seagrass or other habitats and that have no organized structural axis relative to the contours of the shoreline or shelf edge. They are characterized by a roughly circular or oblong shape with a vertical relief of one meter or more in relation to the surrounding seafloor (Figure 2.20). Relict low relief patch reefs with little or no hard coral structure left will be classified as *Pavement*. *Individual Patch Reefs* are larger than or equal to the MMU.



Figure 2.20. The red polygons outline examples of the detailed structure type, *Individual Patch Reef*, as seen in the enhanced satellite imagery in the Canal de Luis Peña West of Culebra Island (left). The underwater photography depicts a close-up of an *Individual Patch Reef* from a shallow snorkel view (middle) and a wider view from a drop-camera (right).

Pavement

Flat, low-relief or sloping solid carbonate rock, often covered with algae, coral, sponges or other sessile vertebrates that are dense enough to partially obscure the underlying surface. On less colonized *Pavement* features, rock may be covered by a thin sand veneer (Figure 2.21).



Figure 2.21. The red polygons outline an example of the detailed structure type, *Pavement*, as seen in the enhanced satellite imagery of Cayo Matojo, off the north coast of Culebra (left). The underwater photography depicts a close-up of colonized *Pavement* from a shallow snorkel view (middle) and a deeper drop-camera view (right).

Pavement with Sand Channels

Have the same defining characteristics as *Pavement*, in addition to having periodic sand/surge channels oriented perpendicular to the *Bank/Shelf Escarpment*. The sand/surge channels of this feature have low vertical relief. This habitat type occurs in areas exposed to moderate wave surge such as the *Bank/Shelf Zone* (Figure 2.22).



Figure 2.22 The red polygons outline an example of the detailed structure type, *Pavement with Sand Channels*, as seen in the enhanced satellite imagery between Cayo Norte and Culebrita Island (left). The underwater photography depicts *Pavement with Sand Channels* from a shallow snorkel view (middle) to a deeper drop-camera view (right).

Reef Rubble

Dead, unstable coral rubble often colonized with filamentous or other macroalgae. The size of the coral rubble can range from large broken coral colonies (such as *Acropora palmata* corals) to smaller cobble sized coral fragments (such as *Porites* species). This habitat often occurs landward of well-developed reef formations in the *Reef Crest*, *Back Reef* or *Reef Flat* zones. Less often, *Reef Rubble* can occur in low density aggregations on broad offshore sand areas (Figure 2.23).



Figure 2.23. The red polygons outline an example of the detailed structure type, *Reef Rubble*, as seen in the enhanced satellite imagery of a reef flat outside Culebra Island (left). The underwater photography depicts large pieces of partly solidified reef rubble (middle) and unstable reef rubble on underlying sand bottom with a cover of macroalgae (right).

Rock/Boulder

Solid carbonate or igneous bedrock extending offshore from land, or aggregations of boulders that have been broken off and were transported from their native bedrock by erosional forces (Figure 2.24). Individual boulders vary in diameter >0.256 m as defined by the Wentworth scale (Wentworth, 1922).



Figure 2.24. The red polygon outline an example of the detailed structure type, *Rock/Boulder*, as seen in the enhanced satellite imagery of the shoreline/intertidal zone of Cayo Norte, north of Culebra Island (left). The underwater photography depicts an example of carbonate bedrock (middle), and an example of an aggregation of igneous boulders (right).

Spur and Groove

Structure having alternating sand and coral formations that are oriented perpendicular to the shore or reef crest (Figure 2.25). The coral formations (spurs) of this feature typically have a high vertical relief (approximately 1 meter or more) relative to pavement with sand channels and are separated from each other by 1-5 meters of sand or hardbottom (grooves), although the height and width of these elements may vary considerably. This habitat type typically occurs in the *Fore Reef* or *Bank/Shelf Escarpment* zone.



Figure 2.25. The red polygon outlines an example of the detailed structure type, *Spur and Groove*, as seen in the enhanced satellite imagery offshore of Culebra Island (left). The underwater photography depicts a stony coral dominated spur with a sandy groove (middle), and an algae dominated spur with a pavement groove (right).

Unconsolidated Sediment

Areas on the seafloor consisting of unconsolidated sediments and covered with less than 10% hardbottom. Detailed structure classes include: *Mud*, *Rhodoliths*, *Rhodoliths with Scattered Coral and Rock*, *Sand* and *Sand with Scattered Coral and Rock*.

Mud

Fine sediment often associated with river discharge and build-up of organic material in areas sheltered from high-energy waves and currents (Figure 2.26). Particle sizes range from $< 1/256 - 1/16$ mm (Wentworth, 1922).



Figure 2.26. The red polygon outlines an example of the detailed structure type, *Mud*, as seen in the enhanced satellite imagery of the lagoon inside Culebra Island (left). The underwater photography depicts mud with invertebrates and burrows (middle), and an example of the mapper testing the composition of the sediments (right).

Rhodoliths

Rhodoliths are coralline red algae that have formed unattached hard calcareous nodules, averaging approximately 6 cm in diameter (Foster, 2001). *Rhodoliths* are commonly found in offshore bank/shelf areas and can form thick rhodolith beds that can eventually deposit and cement into pavement. If the rhodoliths covers $< 10\%$ of a polygon in a sandy area it is classified as sand. Since rhodoliths are unattached to the seafloor and mobile, their distributions can change quantifiably from year to year. The density of the rhodolith aggregations can be shown in the habitat map by combining the *Rhodolith* polygon with the percent major biological cover attribute (Figure 2.27).



Figure 2.27. The northern side of the red polygon outlines an example of the detailed structure type, *Rhodoliths*, as seen in the enhanced satellite imagery on the shelf between Culebra Island and Puerto Rico. The underwater photography (middle) depicts a dense rhodolith bed (*Rhodoliths*, *Biological Cover Algae*, *Percent Cover* 90%-100%), and (right) scattered rhodoliths completely covered in turf algae (*Rhodoliths*, *Biological Cover Algae*, *Percent Cover* 50%-90%).

Rhodoliths with Scattered Coral and Rock

Areas on the seafloor where $\geq 10\%$ of the entire polygon is covered by rhodoliths, and $< 10\%$ of the entire polygon is covered by scattered rocks or isolated coral heads that are too small to be delineated individually. If the density of the rocks and/or coral heads is $\geq 10\%$ of the entire polygon's area, then the structure is typically described as *Aggregated Patch Reefs* or *Pavement* depending on the topographic complexity of the hardbottom (Figure 2.28).



Figure 2.28. The red polygon outlines an example of the detailed structure type, *Rhodoliths with Scattered Coral and Rock (RSCR)*, as seen in the enhanced satellite imagery offshore of Culebra Island (left). The underwater photography depicts an example of *RSCR* with soft corals (middle) and an example with *RSCR* with hard corals (right). Live coral cover for *RSCR* was classified as *Unknown* since it was deemed too uncertain to accurately observe coral cover for habitats with $< 10\%$ hardbottom cover.

Sand

Coarse sediment typically found in areas exposed to currents or wave energy (Figure 2.29). Sand habitats may also be covered in seagrass or macroalgae. Particle sizes range from 1/16–64 mm, including pebbles (Wentworth, 1922).



Figure 2.29. The red polygon outlines an example of the detailed structure type, *Sand*, as seen in the enhanced satellite imagery of a lagoon in Culebra Island (left). The underwater photography depicts a close-up of sand with macroalgae cover (middle), and an example of the mapper showing the coarseness of sandy sediments (right).

Sand with Scattered Coral and Rock

Areas where $\geq 10\%$ of the entire polygon is covered by sand and $< 10\%$ of the entire polygon is covered by scattered rocks or small, isolated coral heads that are too small to be delineated individually (Figure 2.30). If the density of small coral heads is $\geq 10\%$ of the entire polygon, this structure type is described as *Aggregated Patch Reefs*.



Figure 2.30. The red polygons outline examples of the detailed structure type, *Sand with Scattered Coral and Rock (SSCR)*, as seen in the satellite imagery of the *Back Reef* of Culebrita Island (left). The underwater photography (middle, right) depicts a close-up of SSCR. Live coral cover for SSCR was classified as *Unknown* since it was deemed too uncertain to accurately observe coral cover for habitats with $< 10\%$ hardbottom cover.

Other Delineations

Any other type of structure not classified as *Coral Reef and Hardbottom* or *Unconsolidated Sediment*, usually related to the terrestrial environment and/or anthropogenic activity. Detailed structure classes include *Land* and *Artificial*.

Artificial

Man-made habitats such as submerged wrecks, large piers, submerged portions of rip-rap jetties, and the shoreline of islands created from dredge spoil (Figure 2.31).



Figure 2.31. The red polygons outline examples of the detailed structure type, *Artificial*, as seen in satellite imagery of the marina at Puerto del Rey, Fajardo (left), and the docks, boat landings, and wreck inside the lagoon of Culebra (middle). The underwater image shows debris from a shipwreck with fish taking refuge (right).

Land

Terrestrial features at or above the spring high tide line (Figure 2.32).



Figure 2.32. The red polygons outline an example of the detailed structure type, *Land*, as seen in the satellite imagery of Cayo del Agua, west of Culebra Island (left). The photographs depict a view of the mountains and coastal lowlands of Northeast Puerto Rico (middle) and the small cays of La Cordillera (right).

Unknown

Major and/or detailed structure in the project area that is indistinguishable in the bathymetry, aerial or satellite imagery due to low data quality (Figure 2.33).

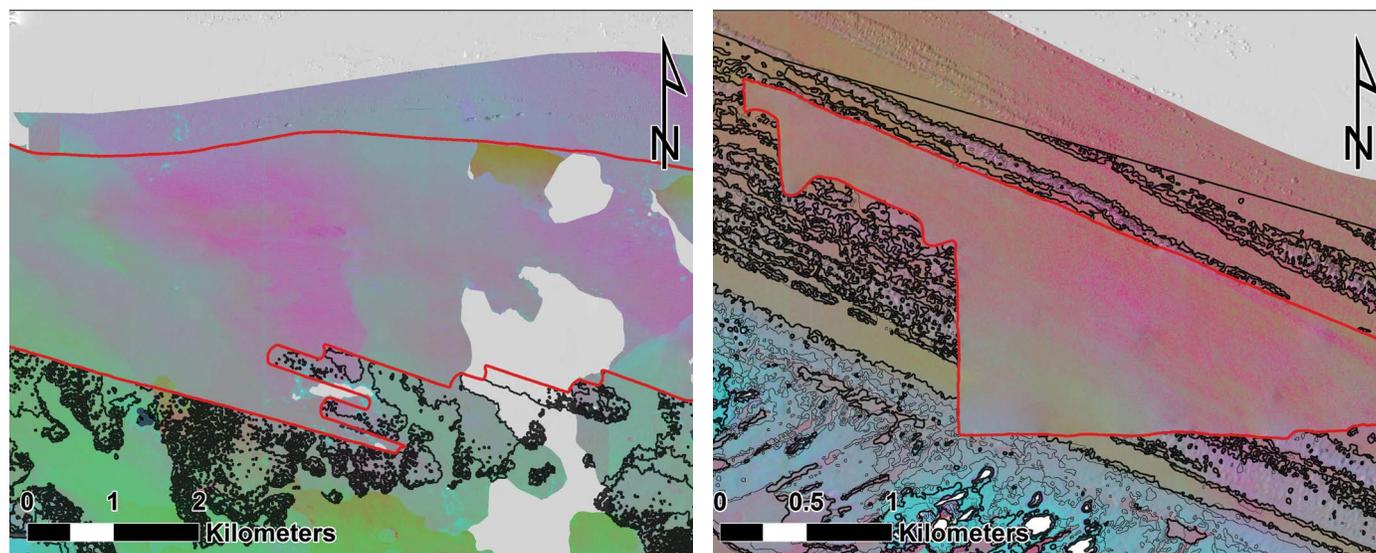


Figure 2.33. The red polygons outline examples of areas with *Unknown* detailed structure types as seen in the enhanced satellite imagery and bathymetry imagery north of Luquillo (left), and north of La Cordillera (right). The areas are classified as *Unknown* due to insufficient remote sensing data caused by deep water, cloud cover, turbid waters and low quality depth data.

2.4. GEOMORPHOLOGICAL STRUCTURE MODIFIERS

2.4.1. Percent Hardbottom Modifier

Percent Hardbottom refers to the amount (i.e., patchiness) of hardbottom structure within a habitat polygon. It does not describe the type of hardbottom habitat that is located within a polygon. This modifier was determined by estimating the percent hardbottom at the scale of the polygon based on the bathymetry model and the observations from the ground validation videos.

Polygons with discontinuous cover of hard bottom and areas of interspersed unconsolidated sediments that were too small to be mapped as a different feature (i.e., smaller than the MMU) were classified as $0\% \leq 10\%$, $10\% \leq 30\%$, $30\% \leq 50\%$, $50\% \leq 70\%$, and $70\% \leq 90\%$ hardbottom. Polygons that were estimated to be almost completely covered by hardbottom were classified as $90\% - 100\%$ hardbottom (Figure 2.34).

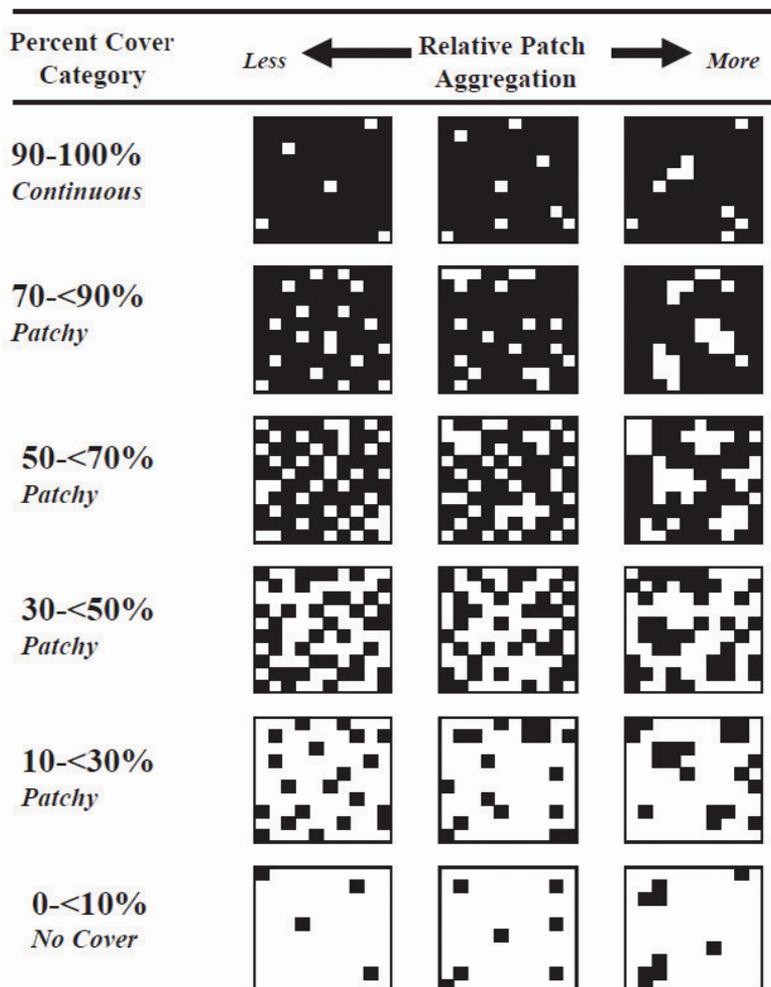


Figure 2.34. This chart outlines the process used to estimate the patchiness when assigning a percent hardbottom and percent biological cover value to a polygon (Kendall, et al., 2001).

2.4.2. Topographic Complexity

Topographic Complexity captures the structural complexity of hardbottom habitats as observed from underwater videos. This allows for a complexity measure at a finer scale than the available multi-resolution depth data (resolution 4 m - 100 m) supported in this project. The *Topographic Complexity* definition includes combinations of both fine scale hard structures like individual hard corals and barrel sponges, as well as larger scale structures such as walls, mounds and ledges. Additional complexity added by soft corals, mangroves, algae and seagrass beds were not included. All soft bottom habitats were classified as *Very Low* complexity. Due to the nature of the visual based classification no quantitative values were assigned to the definitions (CMECS rugosity class has guidelines with quantitative values that could be used in any future efforts that extract terrain models directly from video data).

Very Low

Unconsolidated sediments (Figure 2.35a) or hardbottom (Figure 2.35b) with very low complexity of fine and large scale structures (*example: flat pavement*).

Low

Low complexity (Figure 2.35c) of fine and/or large scale structures (*example: pavement with sand channels, degraded reef with little structure left, low profile aggregated patch reefs*)

Moderate

Moderate complexity (Figure 2.35d) of fine and/or large scale structures (*example: boulders and bedrock or aggregate reefs with some structure left*)

High

High Complexity (Figure 2.35e) of fine and/or large scale structures (*example: large boulders with hard corals, high relief aggregate reefs and patch reefs with high abundance of hard coral structures*)

Very High

Very High Complexity (Figure 2.35f) of fine and/or large scale structures (*example aggregate reefs and patch reefs with vertical walls and cracks, undercut ledges and complex hard coral structures*)



Figure 2.35. *Topographic Complexity.* The underwater photography shows habitats with (a) *Very Low Topographic Complexity* - unconsolidated sediments with *Rhodoliths* covered in macroalgae, (b) *Very Low Topographic Complexity* - pavement with scattered corals, (c) *Low Topographic Complexity* - flattened low relief aggregate reef covered with algae (d) *Moderate Topographic Complexity* - aggregate reef with a mix of live and dead *Acropora* corals, (e) *High Topographic Complexity* - high relief aggregated patch reefs dominated by algae, (f) *Very High Topographic Complexity* - aggregate reef with chasms, overhanging ledges, and large pillars of hard corals with both fine and large scale complex features.

2.5. BIOLOGICAL COVER CLASSES

Biological cover denotes the dominant biological component colonizing the seafloor in a polygon. Habitat features smaller than the MMU (100 m²) were not considered. Five major cover types were identified in the project area (i.e., *Algae*, *Mangrove*, *Seagrass*, *Live Hard and Soft Corals* and *No Cover*) and were combined with three modifiers describing the distribution of the dominant cover within the polygon (i.e., $10\% \leq 50\%$, $50\% \leq 90\%$, and $90\% - 100\%$). Areas where biological cover was indistinguishable from the remote sensing imagery were classified as *Unknown*. It is important to note that this modifier represents a measure of patchiness of the biological cover at the polygon scale. It does not denote the density of organisms seen in the underwater video or photos. For example, a seagrass bed can be described as covering 90%-100% of a given polygon, but may have sparse densities of shoots in the underwater video. Figure 2.42 (pg. 26) illustrates how patchiness was used to assign a biological percent cover.

Major Biological Cover

Algae

Substrates with 10% or greater distribution of any combination of numerous species of red, green, or brown algae. *Algae* may be turf, fleshy, coralline or filamentous species. *Algae* occurs throughout many zones, especially on hardbottom with low coral densities and on unconsolidated sediment in deeper waters (Figure 2.36).



Figure 2.36. The red polygons outline examples of the biological cover, *Algae*, as seen in the enhanced satellite imagery of the northeast bank of Culebra (left). The underwater photography depicts a close-up of coralline algae covering an *Aggregate Reef* (middle) and macroalgae covering a sand flat (right).

Live Coral

Substrates colonized with 10% or greater live reef building corals and other organisms including hard scleractinian corals (e.g., *Acropora* sp.) and soft gorgonian corals (e.g., *Briareum* sp.) (Figure 2.37).



Figure 2.37. The red polygons outline examples of the biological cover, *Live Coral*, as seen in the enhanced satellite imagery of the bank/shelf of Culebra (left). The underwater photography depicts close-ups of aggregate reefs covered by hard corals like the endangered *Acropora cervicornis* (middle) and soft *gorgonian* corals (right).

Mangrove

This habitat is comprised of semi-permanently, seasonally or tidally flooded coastal areas occupied by any species of mangrove (Figure 2.38). Mangrove trees are halophytes (i.e., they thrive in and are especially adapted to salty conditions). In the U.S. Caribbean, there are three species of mangrove trees: red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*), and white mangrove (*Laguncularia racemosa*); another tree, buttonwood (*Conocarpus erectus*), is often associated with the *Mangrove* formation. Red mangroves grow at the water's edge and in the tidal zone. Black mangroves and white mangroves grow further inland where flooding occurs only during the highest tides.



Figure 2.38. The red polygons outline examples of the biological cover, *Mangrove*, as seen in the satellite imagery of the intertidal zone of Culebra (left). The photographs depict close-ups of mangrove stalks and leaves above the tideline (middle), and the roots below tideline (right).

Seagrass

Habitat dominated by any single species of seagrass (e.g., *Syringodium* sp., *Thalassia* sp., *Halophila* sp.) or a combination of several species (Figure 2.39).



Figure 2.39. The red polygons outline examples of the biological cover, *Seagrass*, as seen in the enhanced satellite imagery of the bank/shelf of Culebra (left). The underwater photography depicts a close-up of seagrasses with a foraging queen conch from a snorkel view (middle), and seagrasses from a deeper drop-camera view (right).

No Cover

Substrates with less than 10% of any biological cover type. This habitat is usually associated with *Mud* or *Sand*. *No Cover* is always estimated at 90%-100% of the bottom (Figure 2.40).



Figure 2.40. The red polygon outline examples of the biological cover, *No Cover*, as seen in the satellite imagery of a lagoon in Culebra (left). The underwater photograph depicts a stingray resting on a sand flat with no biological cover (right).

Unclassified

A different biological cover type, such as upland or deciduous forest, that is not included in this habitat classification scheme (Figure 2.41). Most often used for polygons classified as *Land*.

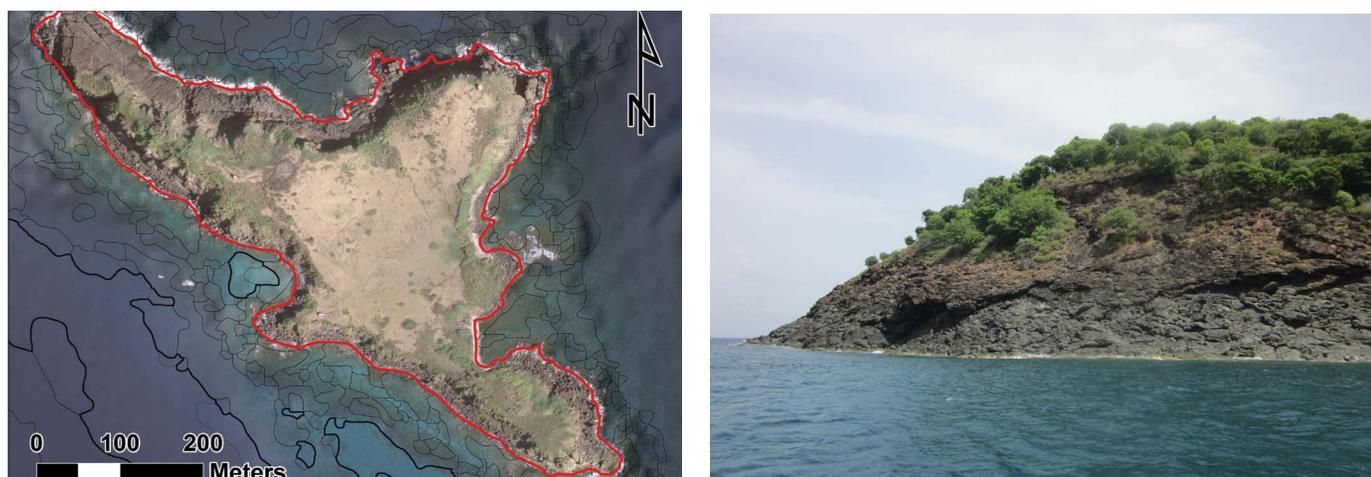


Figure 2.41. The red polygon outline examples of the biological cover, *Unclassified*, as seen in the satellite imagery of Cayo Lobo (left). The photograph depicts the *Unclassified* biological cover above the shoreline of Cayo Norte (right).

Percent Major Cover

The major biological cover type of the polygon was modified by five additional classes ($10\% \leq 50\%$, $50\% \leq 90\%$, $90\% - 100\%$, *Unknown*, and *Not Applicable*) that estimate the percent of the polygon covered by the biological cover class. Polygons with less than 10% of a major biological cover were not considered and classified as having *No Cover*.

$10\% \leq 50\%$

Patchy cover of the major biological type with breaks in coverage that are too diffuse to delineate or too small to be mapped as a different feature (i.e., smaller than the MMU). Overall cover of the major biological type is estimated to cover $10\% \leq 50\%$ of the entire polygon feature (Figure 2.42).

$50\% \leq 90\%$

Discontinuous cover of the major biological type with breaks in coverage that are too diffuse to delineate or too small to be mapped as a different feature (i.e., smaller than the MMU). Overall cover of the major biological type is estimated to cover $50\% \leq 90\%$ of the entire polygon feature (Figure 2.42).

$90\% - 100\%$

Continuous major biological cover type covering 90% or greater of the seafloor (Figure 2.42).

Not Applicable (N/A)

An estimate of percent cover is not appropriate for this particular major biological cover class (e.g., for *Land* polygons). Regularly accompanies the use of *Unclassified* as the major biological cover.

Unknown

Percent estimate of the biological cover that is indistinguishable in the remote sensing imagery.

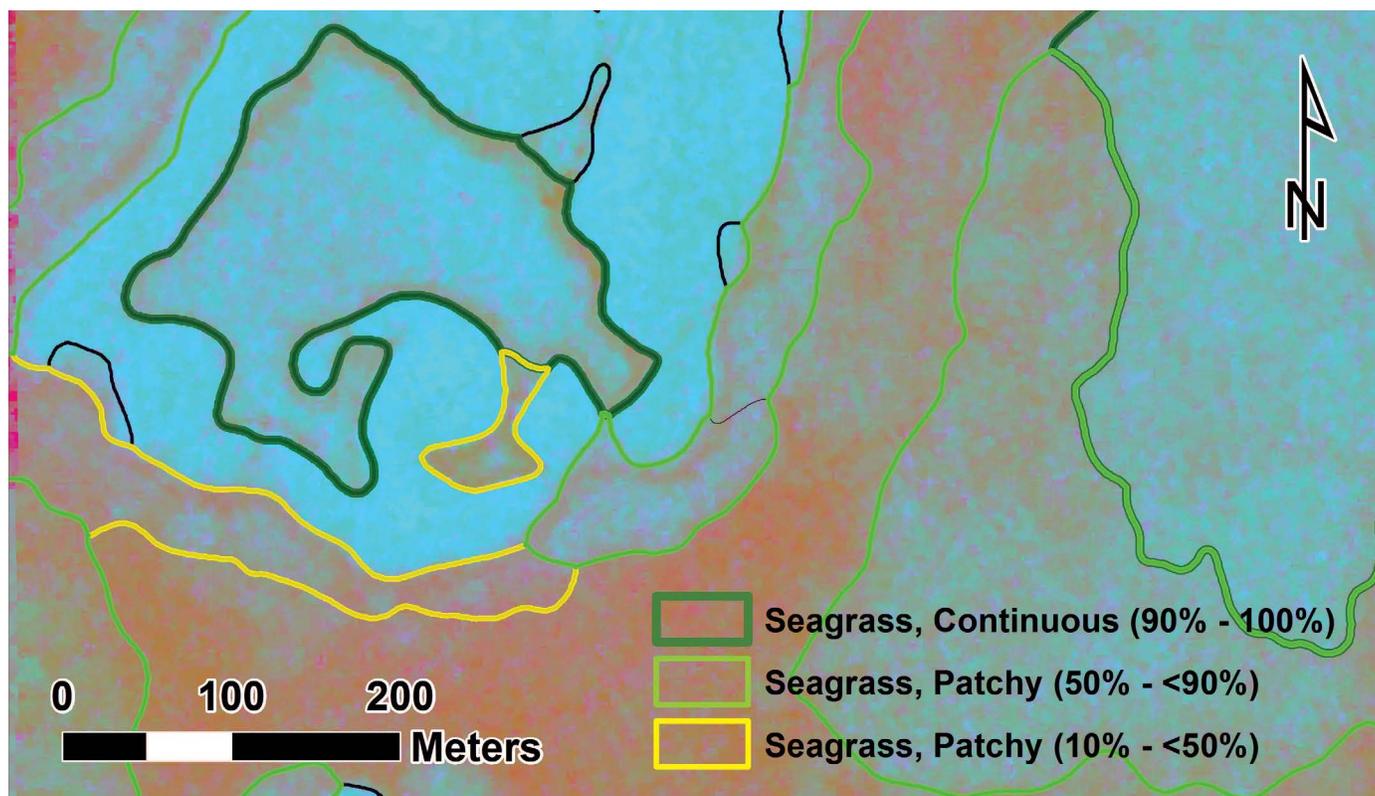


Figure 2.42. The polygons of this enhanced satellite imagery symbolize the *Percent Major Cover* for seagrass patches. The speckled blue and red shaded areas across the map represent the seagrass (the more blue the more seagrass, the more red the more uncolonized sand) and the solid light blue areas represent pavement with soft corals. The reef can also be recognized by the thin sand halo (red), separating the reef and the seagrass beds.

2.6. LIVE CORAL COVER CLASSES

Live hard and soft coral cover were assessed from ground validation videos, and then applied across the seascape using geostatistical modelling and remote sensing data. The percent live coral cover class includes both hard corals (*scleractinian order*) and soft coral (*gorgonian order*). In addition, a dominant coral type modifier was included to identify if the live coral cover was dominated by hard or soft corals or a mix of them both.

2.6.1. Percent Coral Cover

The *Percent Live Coral Cover* attribute describes the hardbottom area of the seafloor that is colonized by live hard and soft corals, as interpreted from a video camera looking straight down at the sea floor from a height of 1-2 meters. To get an estimate of total percent coral cover on the scale of the polygon level (i.e., $>100 \text{ m}^2$) in areas with patchy hardbottom cover, the percent coral cover needs to be combined with the percent hardbottom modifier. For example, if the percent coral cover is classified as 10% - 50% in a polygon delineating an area with *Aggregated Patch Reefs*, and the percent hardbottom cover is 10% - 30%, the total coral cover at the scale of the polygon can vary between 1% - 15% (from 10% hardbottom and 10% Live coral = 1% Coral Cover on the polygons level, to 30% hardbottom and 50% coral = 15% total coral cover). It is important to note that the percent coral cover class is different from percent biological cover, which denotes the patchiness of biological cover at the scale of the polygon including both hard and soft bottom.



An aggregate reef abundant with fish and covered by a mix of hard and soft corals.

Since the percent coral cover is assessed remotely from a “birds eye view,” it also includes the canopy of the corals, most noticeable are branching species such as *gorgonians*. The reported coral cover including the canopy might differ significantly from the percent coral cover counting only the holdfast, as documented in many diver conducted mapping and monitoring programs. For hard coral dominated habitats, the reported percent coral cover is more consistent with surveys counting only the holdfast compared with soft *gorgonian* coral dominated areas, with the exception of a few healthy patches of branching *Acropora* coral dominated reefs.

Four classes were used to describe the combined abundance of hard and soft corals: $0\% \leq 10\%$, $10\% \leq 50\%$, $50\% \leq 90\%$, and $90\% - 100\%$.

$0\% \leq 10\%$

Live hard and soft corals colonize less than 10% of the hardbottom (Figure 2.43). These habitats may be heavily degraded reefs or hardbottom with very patchy coral cover, including endangered *Acropora* species.



Figure 2.43. The underwater photography depicts habitats with $0\% \leq 10\%$ Percent Coral Cover, as seen in the image of bedrock (*Rock/Boulder*) colonized by gorgonians (left) and in the image of pavement dominated by macro algae with individual hard corals present (right).

$10\% \leq 50\%$

Live hard and soft corals colonize between 10% and 50% of the hardbottom as seen in the underwater video (Figure 2.44). These habitats may be predominantly covered with dead coral or algae, but still have large patches of live coral.

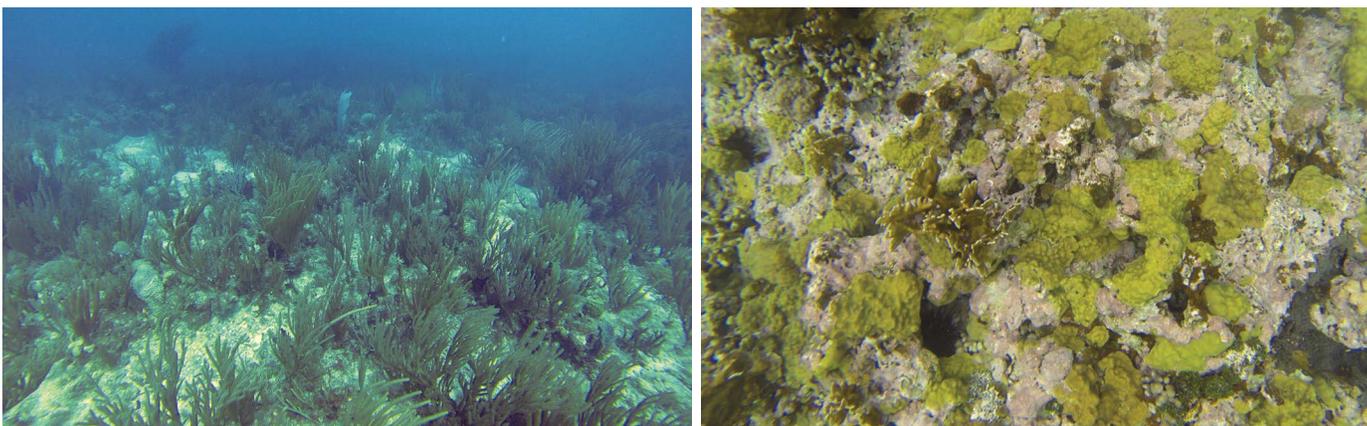


Figure 2.44. The underwater photography depicts habitats with $10\% \leq 50\%$ Percent Coral Cover, as seen in this image of pavement partly covered with live soft coral (left), and the downward facing image of an aggregate reef with patches of hard corals mixed with coralline algae and fire coral (*Hydrozoa*) (right). Fire corals are not included in the coral cover estimate.

50% ≤ 90%

Live hard and soft corals colonize between 50% and 90% of the hardbottom as seen in the underwater video (Figure 2.45). Larger areas (>100m²) of hardbottom dominated by live coral were rare across the project area.

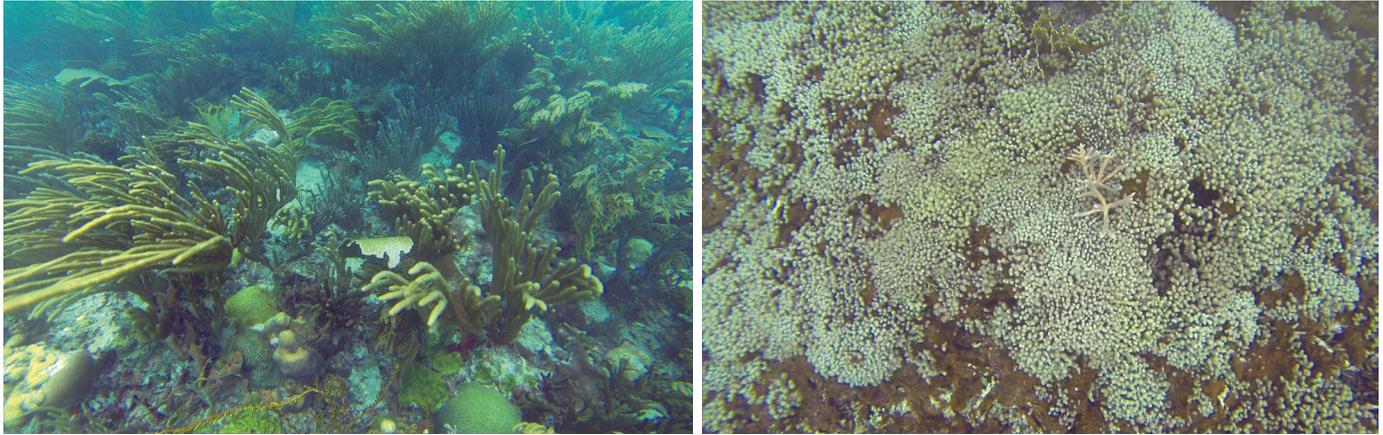


Figure 2.45. The underwater photography depicts habitats with 50% ≤ 90% Percent Coral Cover, as seen in the image of an aggregate reef covered by live hard and soft corals (left) and the downward facing image of an aggregate reef covered by large patches of *Porites* corals (right).

90% < 100%

Continuous live hard and soft corals colonizing 90% or greater of the hardbottom as seen in the underwater video. This habitat was discovered in a few locations where the living *Porites porites* corals almost completely dominated the hardbottom (Figure 2.46), but none were found to be larger than the MMU (100 m²) so this category was not included in the final map.

Unknown

The percent estimate of live hard and soft coral cover is *Unknown*. Coral cover and dominant coral type for the structure categories *Sand with Scattered Coral and Rock*, and *Rhodoliths with Scattered Coral and Rock* were classified as *Unknown*, as it was deemed too uncertain to identify coral cover and type on the very sparse hardbottom surfaces (0% - 10% percent hardbottom).



Figure 2.46. The underwater photography depicts habitats with 90% < 100% Percent Coral Cover, as seen in the image of a reef flat patch almost completely covered by *Porites porites*.

Dominant Coral Type

The dominant coral type was identified for all polygons with more than 10% *hardbottom* cover and with *Percent Coral Cover* greater than 1%. This is different compared to the previous effort by Costa, et al., 2013, where dominant coral type was only assessed for hardbottom with coral cover greater than 10%.

Hard Coral

Live coral cover clearly dominated by hard corals (scleractinians).

Soft Coral

Live coral cover clearly dominated by soft corals (gorgonians).

Mixed Hard/Soft

Mixed cover of both live hard corals (*scleractinians*) and soft corals (*gorgonians*) with no clear dominance of one or the other (less than 10% cover difference) (Figure 2.47).



Figure 2.47. The underwater photographs show examples of habitats classified as scleractinian *Hard Coral* (left), *Mixed Hard/Soft* corals (middle) and gorgonian *Soft Corals* (right) according to the *Dominant Coral Type* modifier.

No Cover

Dominant coral cover was not identified for soft bottom habitats or hardbottom with less than ~1% coral cover. There might still be soft and hard corals present, including corals listed under the ESA such as *Acropora* corals (Figure 2.48).



Figure 2.48. The underwater photographs are examples of the *No Cover* class according to the *Dominant Coral Type* modifier. Softbottom (*Sand*) covered in macroalgae (left) and hardbottom habitat (*Pavement*) with very low or no coral cover <~1% (right).

Unknown

The coral cover is unknown (See description for “*Unknown*” in *Percent Coral Cover* above).

2.7. ADDITIONAL CLASSIFICATIONS

The habitat classification scheme was extended to include additional metrics of ecological importance used to extract information from the high definition underwater videos. These classes are only presented as point data from the ground validation and accuracy assessment videos, and have not been applied together with the remote sensing data to create a map.

2.7.1. Biological Cover Class: Co-Occurring Cover

Co-Occurring Cover describes a biological cover class occupying more than 10% of a benthic habitat area which is dominated by another biological cover class (classified as *Major Cover*, Figure 2.49). For example, a polygon with 60% *Seagrass* and 40% *Algae* would be classified as *Major Cover Seagrass 50-90%* and *Co-Occurring Cover Algae*. As a result, some biota that did not get captured in the *Major Cover* class primarily due to dominant cover of algae got captured here, specifically *Sponges* and *Zoanthids*. We also captured sites where seagrass and algae were competing with one another.



Figure 2.49. The underwater photographs are examples of *Co-occurring Cover* types, as seen in the examples (left) a reef with *Major Biological Cover Algae* and *Co-occurring Cover Zoanthids*, (middle) Reef Rubble with *Major Biological Cover Algae* and *Co-occurring Cover Seagrass*, (right) Rhodoliths with a *Major Biological Cover of Algae* and a *Co-occurring Cover of Sponges*.

2.7.2. Visibility

The *Visibility* category was added to each ground validation and accuracy assessment site to describe the water clarity at the time of the data collection. This category can help the user understand the confidence in the mapper's classifications and may be a useful metric for mapping threats to the health of coral reef ecosystems (Figure 2.50).

Low Visibility - visibility less than 3 meters, as observed from the underwater video

Moderate Visibility -visibility 3-10 meters, as observed from the underwater video

High Visibility -visibility greater than 10 meters, as observed from the underwater video



Figure 2.50. Seagrass habitat in *Low Visibility* waters (right), *Pavement* with soft corals in *Moderate Visibility* waters (middle) and *Spur and Groove* habitats in *High Visibility* waters (left). In the final GV data set high and moderate visibility was merged as the consistency in the interpretation between these two categories was deemed to be insufficient.

2.7.3. *Acropora*

Presence and absence data for *Acropora palmata* and *Acropora cervicornis* were recorded from observations of each ground validation and accuracy assessment video (Figure 2.51). In addition, comments were recorded for sites with larger aggregations. Only live *Acropora* were considered present and no consistent data was recorded regarding the locations of dead *Acropora*. There could still be live *Acropora* present nearby in areas where an absence was recorded in the videos since the video only captures a relatively small portion of the seafloor. Both *Acropora palmata* and *cervicornis* species are listed under the Endangered Species Act.

Figure 2.51. Elkhorn coral (*Acropora palmata*, top) and Staghorn coral (*Acropora cervicornis*, bottom).



2.7.4. Fauna Presence

The *Fauna* category was used to record the presence of fish, turtles and mammals during the ground validation and accuracy assessment efforts. Our main categories were “*Groupers*”, “*Sharks*”, “*Rays*”, “*Lion Fish*”, “*Lobsters*”, “*Turtles*” and “*Large Other*” (Figure 2.52). *Large Other* could include mammals like dolphins or manatees, large individual fish, or large aggregations of fish. This designation was followed by a comment specifying the nature of the observation. Only fish observations were made in the “*Large Other*” category during the field work, so it was changed to “*Large Fish*” in the final data set.



Figure 2.52. The underwater photographs are examples of *Fauna* from the Northeast Reserve, as seen in the images of a lionfish (left), a nurse shark (middle), and a green sea turtle (right).

2.7.5. Habitat Overview

In order to compile the habitat information from the different attributes of the habitat scheme described in this chapter into one simplified habitat map, a “habitat overview” class was created. The intention of this class is to give an overview of the habitats in the project area. This simplified habitat class is used in the Results and Discussion Chapter 5. section to describe the habitats in this report. A key to translate between the overview and the classification scheme is found in Table 2.2.

Table 2.2. Key to translate the “habitat overview” to the classification scheme.

Habitat Overview Attribute	Definition
Coral Reef (High Relief, High Coral)	Coral Reef and Hardbottom; Coral Cover >10%; Moderate-Very High Topographic Complexity
Coral Reef (High Relief, Low Coral)	Coral Reef and Hardbottom; Coral Cover <10%; Moderate-Very High Topographic Complexity
Coral Reef (Low Relief, High Coral)	Coral Reef and Hardbottom; Coral Cover >10%; Very Low - Low Topographic Complexity
Coral Reef (Low Relief, Low Coral)	Coral Reef and Hardbottom; Coral Cover <10%; Very Low - Low Topographic Complexity
Seagrass (Continuous)	Sand, Mud or Reef Rubble; Seagrass (Continuous (90% - 100%))
Seagrass (Patchy)	Sand, Mud or Reef Rubble; Seagrass (Patchy (10% - <90%))
Algae (Continuous)	Sand, Mud or Rhodoliths; Algae (Continuous (90% - 100%))
Algae (Patchy)	Sand, Mud or Rhodoliths; Algae (Patchy (10% - <90%))
Mangrove (Continuous)	Sand or Mud; Mangrove (Continuous (90% - 100%))
Mangrove (Patchy)	Sand or Mud; Mangrove (Patchy (10% - <90%))
Sand	Sand; No Biological Cover / Unknown Cover
Mud	Mud; No Biological Cover / Unknown Cover
Unknown	Unknown Area

Table 2.3. This table shows a crosswalk between the Biogeography Branch Benthic Habitat Classification Scheme and the US Coastal and Marine Ecological Classification (CMECS). It can be used to translate the habitat scheme described in this chapter to CMECS.

GEOGRAPHIC ZONE	CMECS	CMECS Code	Relationship	Confidence
Back Reef	Back Reef- Coral Reef Zone (Modifier)	(CRZ01)	Equal	Certain
Bank/Shelf	Bank/Shelf - Coral Reef Zone (Modifier)	(CRZ02)	Equal	Certain
Bank/Shelf Escarpment	Bank/Shelf Escarpment - Coral Reef Zone (Modifier)	(CRZ03)	Equal	Certain
Channel	Pass/Lagoon Channel - Level 2 Geoform Type (GC)	Gg1.9.1	Equal	Certain
Dredged	Dredged - Anthropogenic Impact (Modifier)	(AI04)	Equal	Certain
Fore Reef	Fore Reef - Coral Reef Zone (Modifier)	(CRZ04)	Equal	Certain
Lagoon	Lagoon - Coral Reef Zone (Modifier)	(CRZ05)	Equal	Certain
Land	No Equivalent		No Equivalent	Certain
Reef Crest	Reef Crest - Coral Reef Zone (Modifier)	(CRZ06)	Equal	Certain
Reef Flat	Reef Flat - Coral Reef Zone (Modifier)	(CRZ07)	Equal	Certain
Reef Ridge Complex	Reef Ridge Complex - Coral Reef Zone (Modifier)		Equal	Certain
Salt Pond	Salt Pond - Level 1 or 2 Geoform (GC)	Gg3.32	Equal	Certain
Shoreline Intertidal	Shore Complex - Level 1 Geoform (GC)	Gp7	Nearly Equal	Certain
Unknown	Unknown	0		
MAJOR STRUCTURE	CMECS	CMECS Code	Relationship	Confidence
Coral Reef and Hardbottom	Rock Substrate - Substrate Class (SC) AND Coral Reef Substrate - Substrate Subclass (SC)	Gg2.5, Gg1.50	Greater Than	Certain
Unconsolidated Sediments	Unconsolidated Mineral Substrate - Substrate Class (SC)	S1.2	Greater Than	Certain
Other Delineations			No Equivalent	Certain
Unknown	Unknown (Mapping Convention)	0		
GEOMORPHOLOGICAL STRUCTURE	CMECS	CMECS Code	Relationship	Confidence
Aggregate Reef	Aggregate Coral Reef- Level 1 and Level 2 Geoform Type (GC)	Gg2.5.1	Equal	Certain
Aggregated Patch Reefs	Patch Coral Reef - Level 1 and Level 2 Geoform Type (GC) Patchiness (Modifier)	Gg2.5.9(PC##)	Equal	Certain
Artificial	Anthropogenic - Geoform Origin (GC)	Gg3	Equal	Certain
Individual Patch Reef	Patch Coral Reef - Level 1 and Level 2 Geoform Type (GC)	Gg2.5.9	Equal	Certain
Land	No Equivalent	NULL	No Equivalent	Certain
Mud	Area - Level 1 and 2 Geoform (GC) AND Carbonate - Substrate Descriptor (Modifier)	S1.2.2.5	Equal	Certain
Pavement	Pavement Area - Level 1 and 2 Geoform (GC) AND Carbonate - Substrate Descriptor (Modifier)	Gg1.44(SD01)	Equal	Certain
Pavement with Sand Channels	Pavement Area - Level 1 and 2 Geoform (GC) AND Carbonate - Substrate Descriptor (Modifier) WITH Co-Occurring Element Sand Channel - Level 2 Geoform (GC)	Gg1.44(SD01), Gg1.9.2	Equal	Certain
Reef Rubble	Rubble Area - Level 1 Geoform (GC) AND Coral Rubble - Substrate Subclass (SC)	S2.2.2	Equal	Certain
Rhodoliths	Rhodolith Substrate - Substrate Subclass (SC)	S2.1.2	Equal	Certain
Rhodoliths with Scattered Coral and Rock	Rhodolith Substrate - Substrate Subclass (SC) WITH Co-Occurring Element Coral Head - Level 2 Geoform Type (GC) WITH Co-occurring Element Boulder - Subgroup (SC)	S2.1.2, S2.2.2, S1.1	Equal	Certain
Rock/Boulder	Rock Outcrop - Level 1 Geoform (GC)	Gg1.7	Greater Than	Certain
Sand	Sand - Substrate Group (SC)	S1.2.2.2	Nearly Equal	Certain
Sand with Scattered Coral and Rock	Sand - Substrate Group (SC) WITH Co-Occurring Element Coral Head - Level 2 Geoform Type (GC) AND/OR Co-Occurring Element Boulder - Subgroup (SC)	S1.2.2.2, S2.2.2, S1.1	Equivalent	Certain
Spur and Groove	Spur and Groove Coral Reef- Level 1 and Level 2 Geoform Type (GC)	Gg2.5.11	Equal	Certain
Unknown	Unknown (Mapping Convention)	0		
% HARDBOTTOM	CMECS	CMECS Code	Relationship	Confidence
0% - <10%	0% - <10% User Added Modifier Unit	S1.1(PC01-PC02)	Supplemental	Certain
10% - <30%	10% - <30% User Added Modifier Unit	S1.1(PC03-PC04)	Supplemental	Certain
30% - <50%	30% - <50% User Added Modifier Unit	S1.1(PC05-PC06)	Supplemental	Certain
50% - <70%	50% - <70% User Added Modifier Unit	S1.1(PC07-PC08)	Supplemental	Certain
70% - <90%	70% - <90% User Added Modifier Unit	S1.1(PC09-PC10)	Supplemental	Certain
90% - 100%	90% - 100% User Added Modifier Unit	S1.1(PC11)	Supplemental	Certain
N/A	N/A			
Unknown	Unknown (Mapping Convention)	0		

Table 2.3. cont.

TOPOGRAPHIC COMPLEXITY	CMECS	CMECS Code	Relationship	Confidence
Very Low	Very Low - Seafloor Rugosity (Modifier)	(SR01)	Greater Than	Not Certain
Low	Low - Seafloor Rugosity (Modifier)	(SR02)	Greater Than	Not Certain
Moderate	Moderate - Seafloor Rugosity (Modifier)	(SR03)	Greater Than	Not Certain
High	High - Seafloor Rugosity (Modifier)	(SR04)	Greater Than	Not Certain
Very High	Very High - Seafloor Rugosity (Modifier)	(SR05)	Greater Than	Not Certain
N/A	N/A			
Unknown	Unknown (Mapping Convention)	0		
BIOLOGICAL COVER	CMECS	CMECS Code	Relationship	Confidence
Algae	Benthic Macroalgae - Biotic Subclass (BC)	B2.5.1	Supplemental	Certain
Live Coral	Shallow/Mesophotic Coral Reef Biota - Biotic Subclass (BC)	B2.1.2	Supplemental	Certain
Mangrove	Tidal Mangrove Shrubland- Biotic Group (BC) OR Tidal Mangrove Forest - Biotic Group (BC)	B2.7.1.4, B2.8.1.4	Supplemental	Certain
Seagrass	Seagrass Bed- Biotic Group (BC)	B2.5.2.1	Supplemental	Certain
Sponges	Attached Sponges- Biotic Group (BC)	B2.2.1.21, B2.2.2.26	Supplemental	Certain
Zoanthids	Zoanthids		Added	Certain
No Cover	No Cover	NULL	Equal	Certain
N/A	N/A			
Unknown	Unknown (Mapping Convention)	0		
% BIOLOGICAL COVER	CMECS	CMECS Code	Relationship	Confidence
Patchy (10% - <50%)	Patchy 1 (10% - <50%) - Percent Cover (Modifier)	(PC02-PC06)	Equivalent	Certain
Patchy (50% - <90%)	Patchy 2 (50% - <90%) - Percent Cover (Modifier)	(PC07-PC10)	Equivalent	Certain
Continuous (90% - 100%)	Continuous (90% - 100%) - Percent Cover (Modifier)	(PC11)	Equal	Certain
N/A	N/A			
Unknown	Unknown (Mapping Convention)	0		
CORAL COVER	CMECS	CMECS Code	Relationship	Confidence
0% - <10%	0% - <10% - Percent Cover (Modifier)	B2.1.2 (PC02)	Supplemental	Certain
10% - <50%	10% - <50% - Percent Cover (Modifier)	B2.1.2 (PC03-PC06)	Supplemental	Certain
50% - <90%	50% - <90% - Percent Cover (Modifier)	B2.1.2 (PC07-PC10)	Supplemental	Certain
90% - 100%	90% - 100% - Percent Cover (Modifier)	B2.1.2 (PC11)	Supplemental	Certain
N/A	N/A			
Unknown	Unknown (Mapping Convention)	0		
CORAL TYPE	CMECS	CMECS Code	Relationship	Confidence
Hard Coral	Hard Coral - User Added Modifier Unit		Supplemental	Certain
Soft Coral	Soft Coral - User Added Modifier Unit		Supplemental	Certain
Mixed Hard/Soft	Mixed Hard/Soft - User Added Modifier Unit		Supplemental	Certain
No Cover	No Cover - 0% - <1% - Percent Cover (Modifier)	B2.1.2 (PC01)	Equal	Certain
N/A	N/A			
Unknown	Unknown (Mapping Convention)	0		
VISIBILITY	CMECS	CMECS Code	Relationship	Confidence
Low	Extreme OR High - Turbidity (Modifier)	(TC01 - TC02)	Greater Than	Not Certain
Moderate	Moderate - Turbidity (Modifier)	(TC03)	Greater Than	Not Certain
High	Clear OR Extremely Clear - Turbidity (Modifier)	(TC04 - TC05)	Greater Than	Not Certain
N/A	N/A			
Unknown	Unknown (Mapping Convention)	0		



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CHAPTER 3: METHODS

The ocean and coastline of Northeast Puerto Rico and Culebra Island contains rich, complex and diverse systems of marine habitats that span a range of biological, geological and oceanographic gradients. The region has areas with turbid coastal waters, but also clear waters in areas minimally affected by coastal runoff. These varied environmental conditions affect the quality of satellite and aerial imagery and provide ample challenges for remote sensing based habitat mapping. The area mapped (744 km²) is approximately 10 times larger than other areas of the U.S. Virgin Islands mapped with a minimum mapping unit (MMU) of 100 m² (Costa, et al., 2012, 2013), but smaller than the spatial extents of the lower resolution (MMU = 4,000 m²) habitat maps created for the U.S. Caribbean (Kendall, et al., 2001).



Sunset over the Cabezas de San Juan Natural Reserve.

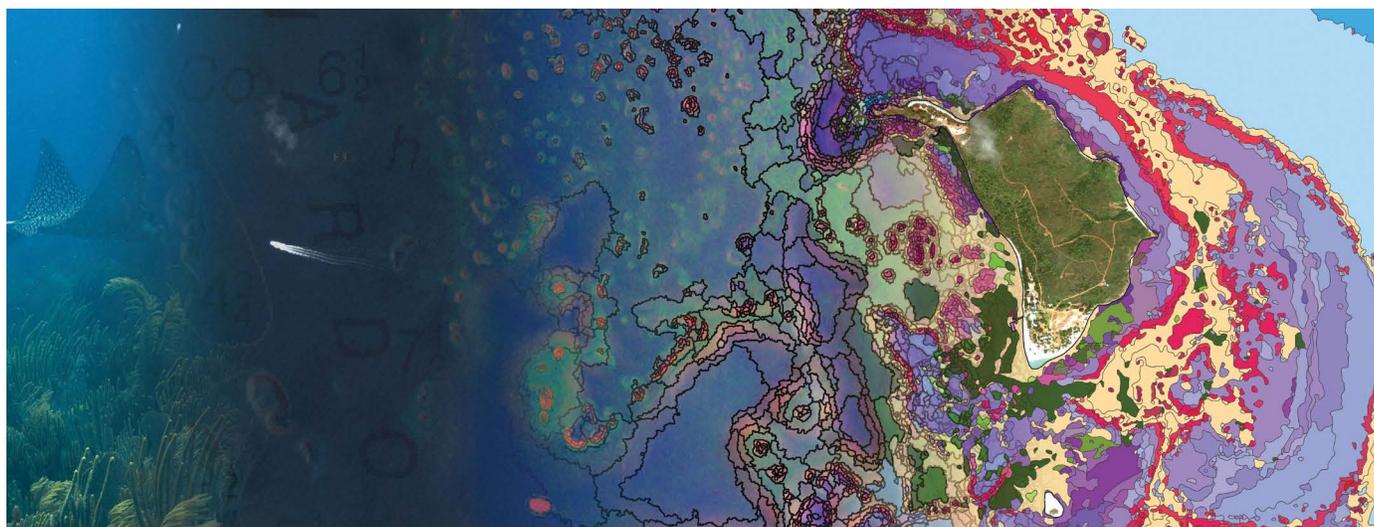


Figure 3.1. High-resolution underwater video and remote sensing imagery combined with automated feature extraction and modeling (left to right) was used to classify benthic marine habitats.

3.1. GENERAL MAPPING APPROACH

Two main habitat mapping methods were applied (1) manual delineation and classification of the *shoreline*, *mangroves*, *lagoons*, and *artificial features* - hereafter referred to as *Shore Complex*, and (2) semi-automated habitat mapping of benthic habitat features outside the shoreline - hereafter referred to as *Open Water*. An overview of the two workflows and how they are combined is found in Figures 3.1 and 3.2. In addition, a Geographic Zone map was manually delineated after the final habitat map was completed. Four types of primary data sources formed the framework of our mapping efforts: (1) hydrographic data spanning the 20th century (1900-2013), (2) Worldview-2 satellite imagery (2011-2013), (3) aerial photographs (2007, 2010) and (4) underwater video and photos (2013, 2014). The satellite imagery and the aerial photographs were collected with passive photo sensors that recorded the sunlight (near infrared and visual spectrum) reflected by atmosphere, land, water and seafloor. The hydrographic data consisted of historical data (lead soundings and single-beam soundings) as well as modern high resolution data (Lidar and multibeam sonar), which were combined into one multi-resolution bathymetry model (seafloor terrain/depth model). The satellite imagery and the bathymetry model were then combined to segment all visible *Open Water* benthic habitat features using feature extraction algorithms, while the aerial photographs were used to manually digitize the *shore complex* areas. The underwater video was used to ground truth the remote sensing data and extract additional ecological data.

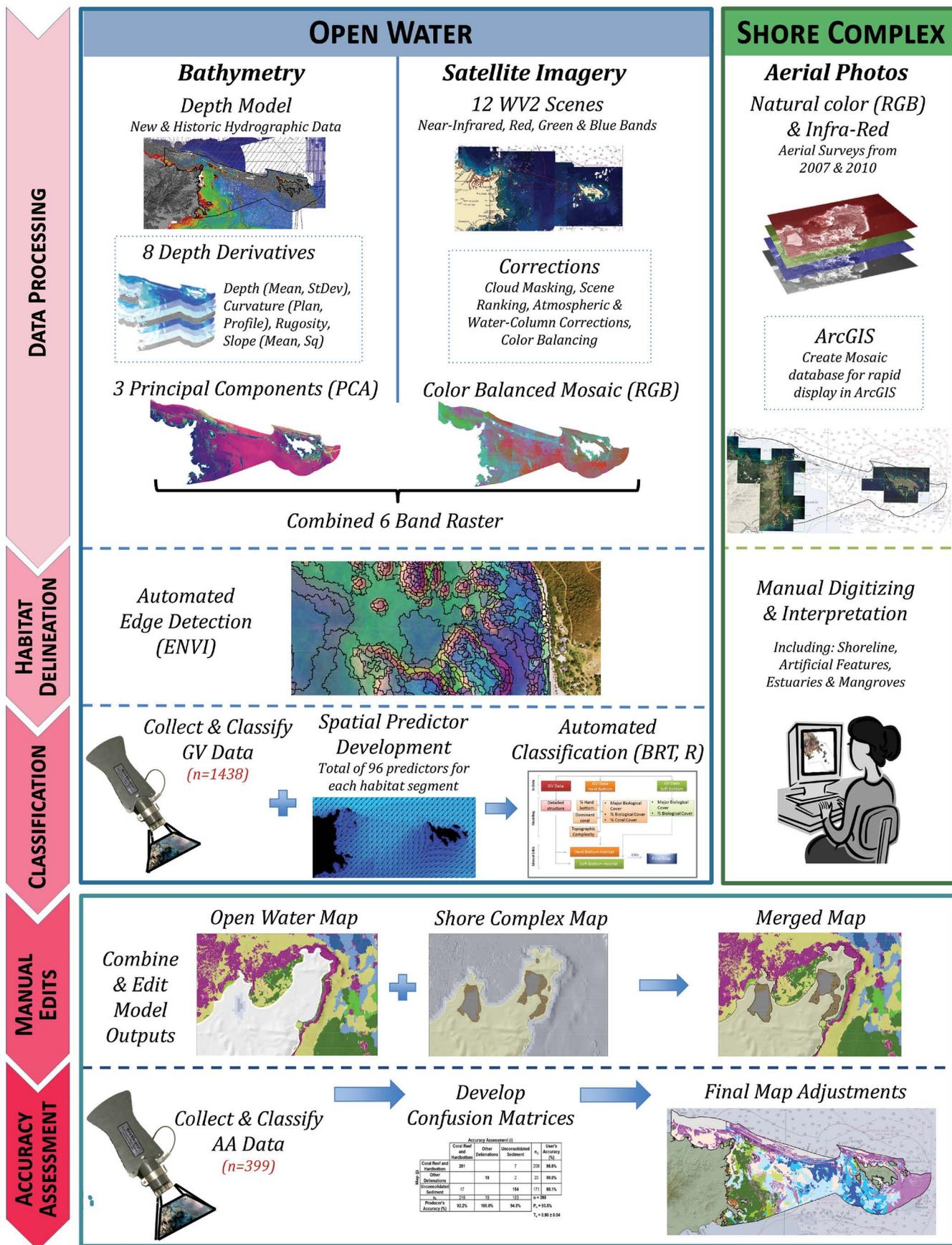


Figure 3.2. The flowchart illustrates the two main processing workflows and provides a visual guide of the methods described in this chapter. *Open water* areas (outside the shoreline) were mapped using semi-automated mapping techniques, while the *shore complex* areas (shoreline, mangroves, lagoons and artificial features) were mapped using manual digitization and classification. The two maps were then combined, accuracy assessed and edited to a final unified product.

Methods Overview

The habitat mapping methods used can be summarized into three main sections (see Figure 3.2 for a visual overview).

Section 1. Manual classification of shore complex areas (Chapter 3.2)

Inshore areas and the shoreline were digitized and classified manually using aerial imagery. The major steps were:

1. *Image acquisition* - High quality aerial imagery from 2007 and 2010 were acquired. Additional imagery was located using Google Earth Pro.
2. *Habitat delineation and classification* - The habitats were manually digitized and classified by a geospatial analyst at a 1:1,000 scale.

Section 2. Semi-automated classification of open water areas (Chapter 3.3)

In order to map the seafloor habitats with high thematic and spatial resolution, a semi-automated habitat mapping workflow was developed based on previous work by NCCOS Biogeography (Costa and Battista, 2013). The major steps were:

1. *Image acquisition* – High-resolution satellite imagery was acquired 2011-2013 covering the geographic extent of the project area. All available depth data from survey years 1900-2013 was collected from various sources.
2. *Image post-processing* – The satellite scenes were processed and color balanced into a high resolution mosaic. The depth data was used to create a multi-resolution bathymetric model.
3. *Habitat boundary delineation* – Habitat features were delineated from a combination of the satellite mosaic and the bathymetric model using edge-detection algorithms.
4. *Ground validation (GV)* - Underwater videos were collected. The video data was manually classified according to the habitat classification scheme (chapter 2)
5. *Habitat modeling* – Spatial predictors were developed and then combined with the unclassified habitat features and the GV data to develop habitat models. A first draft habitat map was created.
6. *Manual edits* – Manual edits were conducted to improve the modelled habitat map.

Section 3. Final map integration and edits (Chapter 3.4)

The two maps and their attribute tables were combined, accuracy assessed and edited together to create the final map. The major steps were:

1. *Combining two maps into one* - The maps were combined into one by clipping the digitized *shore complex* map onto the *open water* map. Any remaining slivers or gaps were filled in.
2. *Manual edits* – The classified habitat segments were edited and quality controlled. Local experts were consulted to verify the map and make additional changes.
3. *Accuracy assessment* - Underwater videos were collected (using a random stratified sampling plan) to independently and quantitatively evaluate the accuracy of the habitat map (see Chapter 4).
4. *Final product creation* - Errors identified during accuracy assessment were corrected and the final habitat map covering Northeast Puerto Rico and Culebra Island was created.
5. *Delivery* - All imagery, maps and videos were uploaded to the NOAA Biomapper GIS portal, and made publicly available for download on the project web page.

In sections 3.1 to 3.3 you will be able to follow these main steps in more detail. Figure 3.2 can be used as a roadmap through most of this chapter. Figure 3.3 shows an overview of different survey methods available for remote sensing, many of which were used in this mapping project (specifically multibeam sonars, Lidar, multispectral satellites and multispectral aerial imagery).

3.2. MANUAL CLASSIFICATION OF SHORE COMPLEX AREAS

Shore complex areas (defined here as the collective name for intertidal and subtidal areas including shorelines, mangroves, lagoons, salt ponds, rivers and land as well as artificial features such as marine infrastructure) were delineated and classified using manual digitizing of aerial photos.

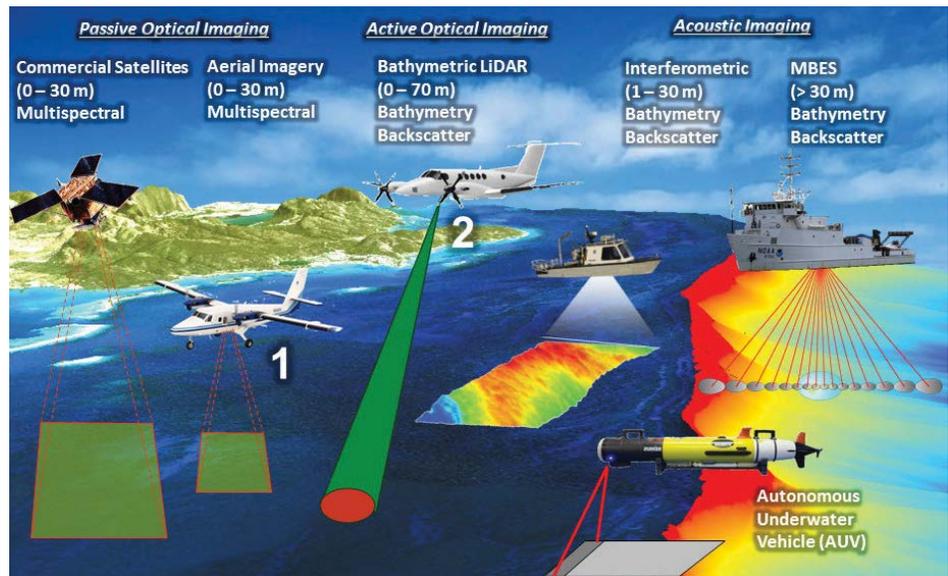


Figure 3.3. The image illustrates various sensors used to map shallow to deep-water marine habitats. This project specifically used multibeam sonars, bathymetric Lidar, multispectral satellites, and multispectral aerial imagery, as well as historical hydrographic surveys (lead soundings and single-beam sonars) and underwater video cameras (drop-camera and snorkel surveys) not shown in this figure.

3.2.1. Imagery Acquisition: Aerial Photographs

The two main imagery sources used to map the *shore complex* areas where aerial photos collected by U.S. Army Corps of Engineers 2007, and aerial photos from Puerto Rico Planning Board surveyed by Fugro Earth Data 2009-2010. We also used Google Earth Pro historical imagery to cover additional areas (Figure 3.4). The 2007 imagery covered Puerto Rico and Culebra Island, and some of the surrounding waters with high resolution orthophotos (0.3 x 0.3 meter) natural color (RGB) and infrared orthophotos. The 2010 imagery covered Puerto Rico and Culebra Island with high resolution (0.3 x 0.3 meter) natural color orthophotos (RGB) but had been cropped along a 500 meter buffer from the shoreline. The survey was conducted with a Leica ADS40-52 Camera and took place from October 31, 2009 thru January 27, 2010.

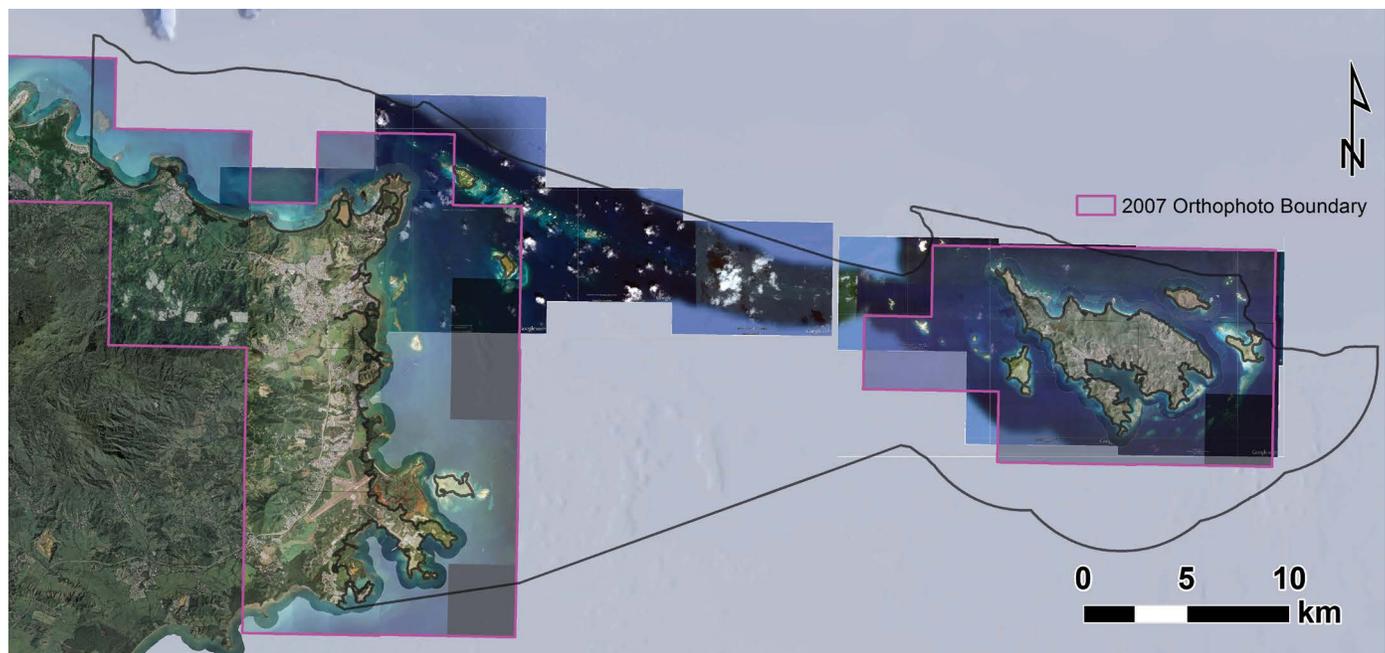


Figure 3.4. Three imagery sources were used to delineate and classify *shore complex* areas: aerial imagery from 2007 and 2010, and Google Earth historical Imagery.

3.2.2. Habitat Delineation and Classification

The shoreline, artificial features (man-made structures and shipwrecks), the mangrove and any intertidal water bodies connected to the ocean were delineated and classified and digitized manually at a scale of 1:1,000. The process to map these features was similar to methods used by the NCCOS Biogeography Branch in other manual mapping efforts (Battista, et al., 2007; Bauer and Kendall, 2010; Kendall, et al., 2001; Zitello, et al., 2009). The main source of imagery used was the aerial photos from 2007, which included an infrared band that was used to identify mangroves among other vegetation (Figure 3.5). We complemented the aerial photos from 2007 with the aerial photos from 2010 together with a selection of older imagery located using Google Earth Pro. The imagery from 2010 was also used to update new features that were not visible in the imagery from 2007 (such as new infrastructure/artificial features and changing landscapes such as eroding sandbars).



Figure 3.5. Shore complex areas were manually delineated and classified using aerial imagery from 2007 and 2010. (a) Shows the RGB bands, (b) show the Infrared band used to identify mangroves and (c) show the final classified *shore complex* map in the Las Cabezas de San Juan Nature Reserve area.

The methods describing the *shore complex* map continues in Chapter 3.4 where the two maps (*shore complex* and *open water*) are combined and finalized.

3.3. SEMI-AUTOMATED CLASSIFICATION OF OPEN WATER AREAS

Open water areas 0 - 35 m deep (defined here as all marine areas outside the shoreline) were delineated and classified using automated feature extraction and modelling techniques then manually edited and re-classified where needed. This section describes the process of preparing remote sensing imagery for this task, the automated segmentation process, and the collection and classification of ground truth field data as well as the modeling method used to classify the extracted habitat segments.

The main reason to use a semi-automated approach compared to the manual mapping method used to map the *Shore Complex* Map is that manually developed benthic habitat maps are: (1) limited to coarser spatial scales and resolutions (because the finer the spatial resolution and scale of delineation, the more time required to make the map); and (2) subjective (because the quality of the maps depends on the effort, experience and expertise of the analyst) (Costa and Battista, 2013). The semi-automated mapping methods described in this chapter were developed to enable a more repeatable and less subjective map, while supporting the mapping of complex coral reef habitats at high thematic and spatial resolutions.

3.3.1. Depth

To address the extreme variations in density and quality of the source hydrographic data available in North-east Puerto Rico, a multi-resolution (4-100 m) geostatistical depth model (bathymetry model) was developed. The model was optimized for automated habitat segmentation which is sensitive to interpolation artifacts that commonly result from gridding heterogeneous data (Figure 3.6). The approach was inspired by (Calder, 2006; Hell and Jakobsson, 2011; Kinlan, et al., 2012). The model covers the full extent of the mapping area and includes a spatially-explicit uncertainty prediction that allows the user to better understand the reliability of the model and the derived habitat maps.

Source data

All available hydrographic data surveyed between 1900 and 2013 were downloaded from NOAA National Geophysical Data Centers (NGDC) on September 4, 2013. Additional Lidar data surveyed in 2001 was acquired from US Army Corps of Engineers Joint Airborne Lidar Bathymetry Technical Center of Expertise. Outcrops (depth = 0 meter) identified in aerial imagery were manually digitized in data poor regions. The hydrographic data spans over 100 years. During that time, survey methods have evolved from lead-line soundings using triangulation for positioning, to single ping sonars, to modern day multibeam sonar and Lidar surveys using GPS technology. The depth data available in the project area is a patchwork of overlapping soundings collected with different precision and resolutions (see Calder, 2006 for full discussion on how the quality of hydrographic soundings have changed over time).

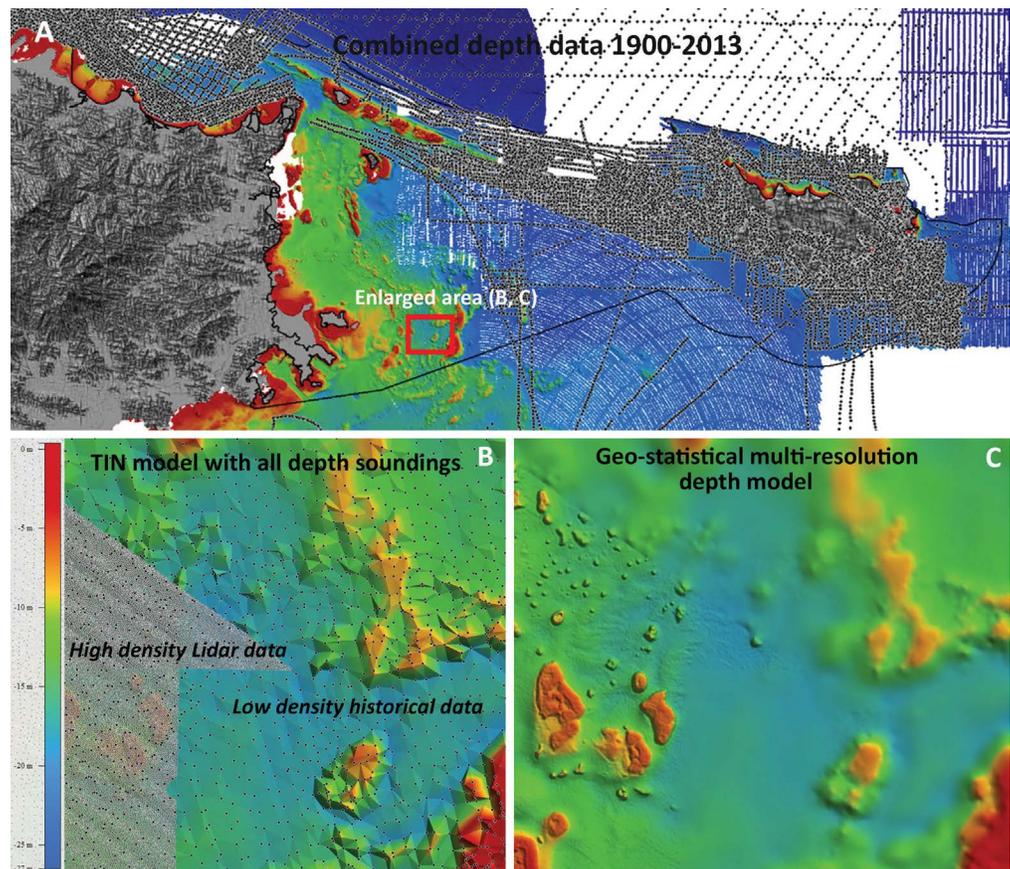


Figure 3.6. All hydrographic data was combined into one data set (A). Bottom left image (B) shows a simple TIN model overlaid with the source data points. There is a sharp contrast in density of soundings where high resolution Lidar data ends (left side) and only historical lead soundings remain (right side). A multi-resolution (4-100 m) kriging model was developed (C) to minimize interpolation artifacts, while preserving the full resolution of the high density data (Lidar, multibeam).

Data Preparation

Coordinate system

All XY data was transformed to NAD 83 UTM zone 20 and the Z values were converted to meters in vertical datum Mean Lower Low Water (MLLW) using Global Mapper.

Depth Adjustments

In order to combine multiple hydrographic surveys, the data was divided into four categories by survey method and year: (1) lead-line surveys (1900-1921); (2) single-beam sonar surveys (1964-1983); (3) multibeam surveys (2007-2013); (4) lidar surveys (2001); and (5) digitized outcrops (2013). The multibeam surveys were determined to be the most reliable data set and therefore used as the reference depth. All other surveys were compared against the multibeam data where overlap existed and the resulting offsets were used to apply depth offsets to the soundings (Table 3.1). Manual edits were made to exclude old and uncertain depth soundings where recent surveys already existed at higher resolution.

Table 3.1. The available hydrographic data was divided into groups based on survey year and method. Overlapping data between the groups were compared with each other and adjusted using the multibeam sonar data as reference depth.

Data type	Depth adjustment [m]	Soundings
Multibeam (2007-2013)	0	483,103
Lidar (2001)	0.443	7,456,869
Singlebeam (1964-1983)	0.583	57,925
Lead Soundings (1900-1921)	0.973	61,819
Digitized Outcrops	0	56

Density classification

The source data was analyzed using the Average Neighbor Tool in ArcGIS to determine the appropriate resolutions of the final model. Three different point density classes were identified in the project area based on the average distance between soundings: high resolution data (4 m), moderate resolution data (20 m), and low resolution data (100 m) (Figure 3.7). In order to save processing time, the source data was divided into high resolution data (multibeam and Lidar only), and low resolution data (all historical surveys as well as a resampled 10 meter resolution version of the multibeam and Lidar surveys).

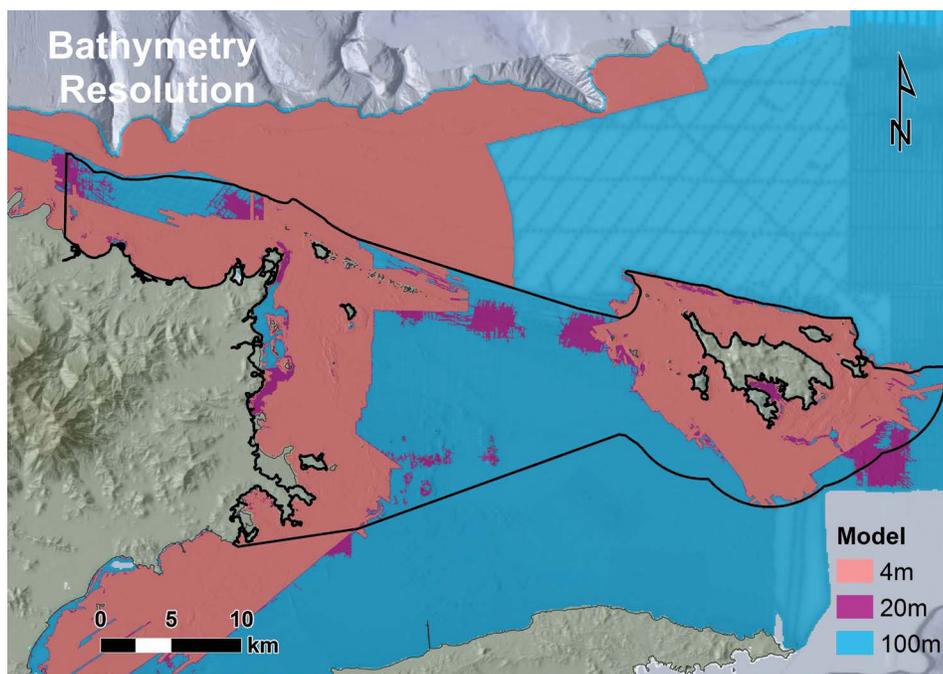


Figure 3.7. The final depth model was a compilation of three different models at 4 m, 20 m and 100 m resolution as shown in this figure. The resolution and extent of each model was driven by the density of the hydrographic source data and the uncertainty of each model.

Transformation

Prior to statistical modeling, depth values were transformed using a logarithmic function to normalize error distributions:

$$Z_{transform} = \ln(Z \times b + a)$$

Equation 1: Z is depth in meters and a and b are the transformation parameters (a = 0.5 m, b = 0.013).

The transformation was based on a standard bathymetric error model formulation (Calder, 2006; IHO, 1998), which improves homogeneity of conditional error variances within local regression and kriging neighborhoods.

Multi-resolution geostatistical modeling

Three kriging models were created: high density (4 meter resolution), moderate density (20 m resolution) and low density (100 m resolution). The models were up-sampled to 4 meters by inserting nodes using a spline function in Surfer. The difference between the models (100 m vs 20 m and 20 m vs 4 m) were computed and extrapolated using simple kriging in ArcGIS to get a smooth transition between the high and low resolution data. Finally the five models were merged into one by stacking the 4 m model on top of the low-resolution models (20 m, 100 m) and sandwiching the two simple kriging models in-between. The final model (Figure 3.8) was sampled at 4 m resolution in order to enable analysis together with high resolution satellite data (section 3.2.2), but the source resolution varied between 4 m and 100 m (Figure 3.7).

Uncertainty Model

Models created using geostatistical kriging also produce uncertainty outputs. In order to calculate the uncertainty for the final multi-resolution bathymetry model, we combined uncertainty outputs from the five sub models and calculated a combined uncertainty model. The uncertainty model was then used to create a half average, a maximum depth, and a minimum depth uncertainty layer at 95% confidence interval (Figure 3.8).

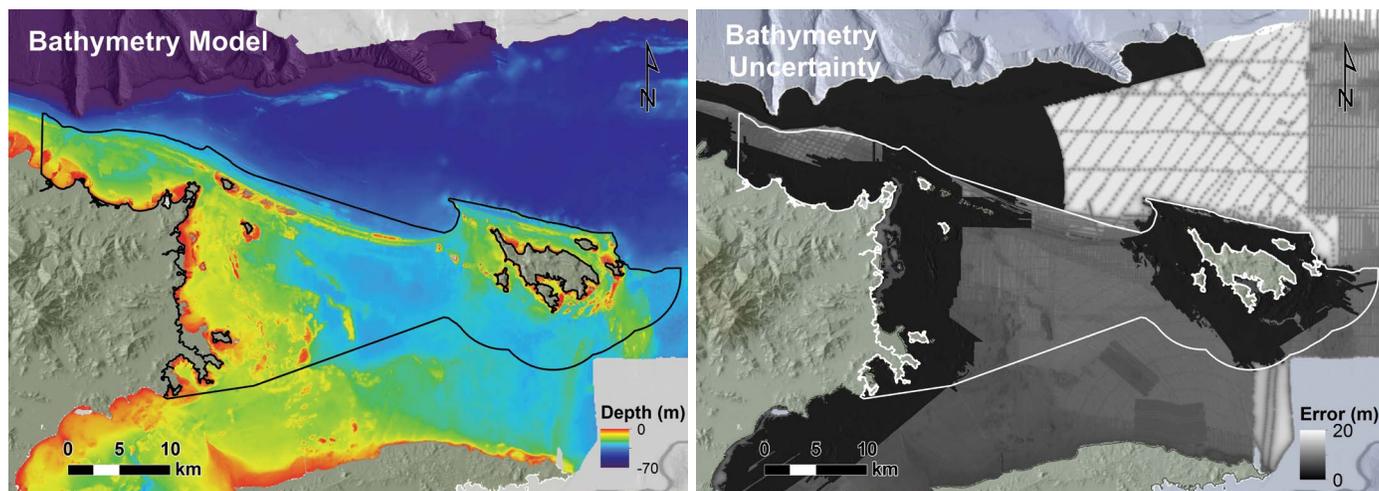


Figure 3.8. The multi-resolution depth model (left) and the associated depth uncertainty model (right).

Creating Derivative Surfaces from Bathymetry

Nine topographic surfaces were derived from the depth model using ArcGIS and DEM Surface Tools (Jenness, 2012); (1) depth, (2) mean depth, (3) standard deviation of depth, (4) curvature, (5) plan curvature, (6) profile curvature, (7) rugosity, (8) slope, and (9) slope of slope. The rasters are described in more detail in Table 3.2. Each raster was calculated using a square 3 x 3 cell neighborhood, where the central pixel in the neighborhood was assigned the calculated value. The individually derived rasters were cropped to the project area, stacked into one nine-band raster, and finally transformed into its first three principal components using the “Principal Components Analysis” (PCA) function in ENVI (Lillesand and Kiefer, 2000; Mather and Koch, 2004). The resulting three-band PCA image contained information that uniquely described the complexity and structure of the seafloor.

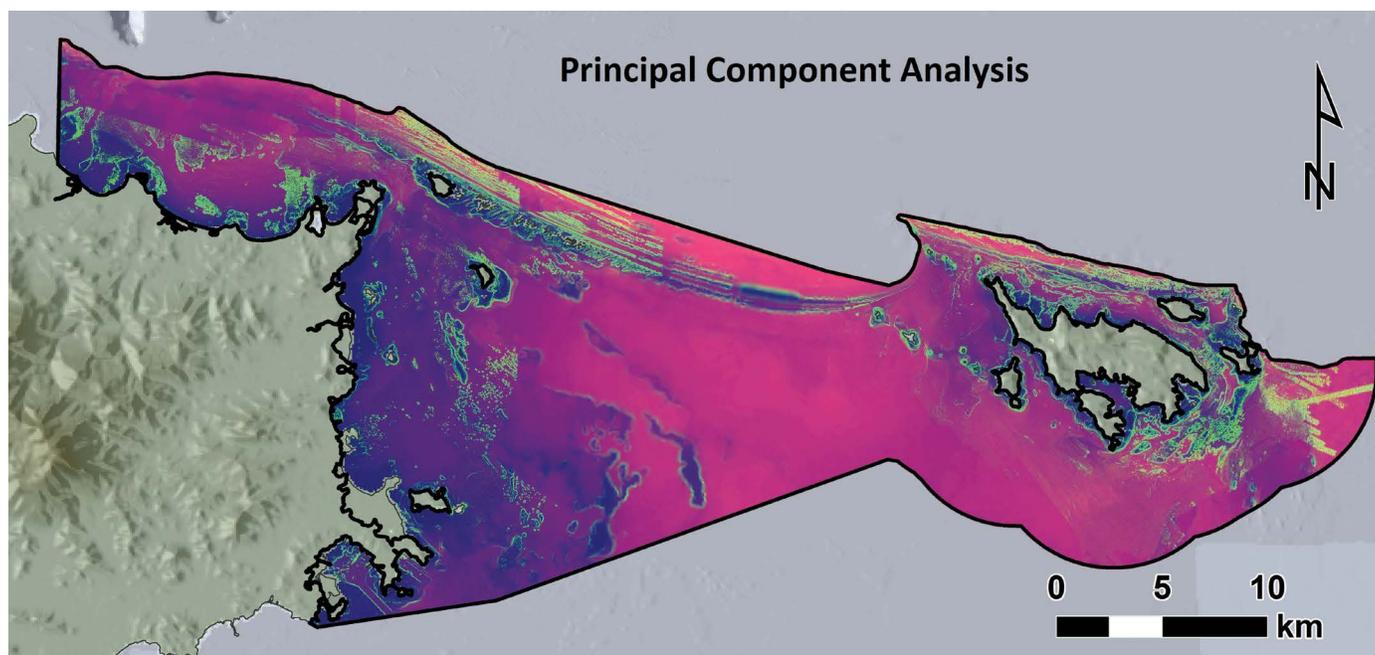


Figure 3.9. The three band Principal Component Analysis (PCA) image was computed from a total of nine topographic derivatives of the depth model and contain information that uniquely described the complexity and structure of the seafloor.

Table 3.2. Descriptions of the eight topographic surfaces derived from the depth model (Pittman, et al., 2009). The nine metrics (including original depth) were then reduced to three principal components (PCA) describing the shape and texture of the seafloor (Figure 3.9).

Topographic Surface	Unit	Description	Tool
Curvature	1/100 z units - = concave + = convex	Rate of change in curvature across the surface highlighting ridges, crests and valleys (3 x 3 cell neighborhood)	Curvature function in ArcGIS 3D Analyst
Plan Curvature	1/100 z units - = concave + = convex	Curvature of the surface perpendicular to the slope direction (3 x 3 cell neighborhood)	Plan curvature function in ArcGIS 3D Analyst
Profile Curvature	1/100 z units - = convex + = concave	Curvature of the surface in the direction (3 x 3 cell neighborhood)	Profile curvature function in ArcGIS 3D Analyst
Depth (Mean)	Meters	Average water depth (3 x 3 cell neighborhood)	Focal statistic in ArcGIS Spatial Analyst
Depth (Standard Deviation)	Meters	Dispersion of water depth values about the mean (3 x 3 cell neighborhood)	Focal statistic in ArcGIS Spatial Analyst
Surface rugosity	Ratio value	Ratio of surface area to planar area (3 x 3 cell neighborhood)	Benthic Terrain Mapper toolbox
Slope	Degrees	Maximum rate of change in slope between cell and 8 neighbors (3 x 3 cell neighborhood)	ArcGIS Spatial Analyst's slope function
Slope of the slope	Degrees of degrees	Maximum rate of maximum slope change between cell and eight neighbors (3 x 3 cell neighborhood)	ArcGIS Spatial Analyst's slope function

3.3.2. Satellite Imagery

Data Acquisition

Digital Globe WorldView-2 satellite images were collected between September 2011 and August 2013 (Table 3.3). A total of 12 satellite scenes were collected in order to acquire sufficient cloud free coverage for the full extent of the project area. Worldview-2 is a high-resolution 8-band multispectral commercial satellite. The satellite operates at an altitude of 770 kilometers and provides 46 cm panchromatic resolution and 1.85 cm 8 band multispectral resolution (Table 3.4). The geolocation error is $< \pm 3.5$ m according to DigitalGlobe.

Imagery Post-Processing

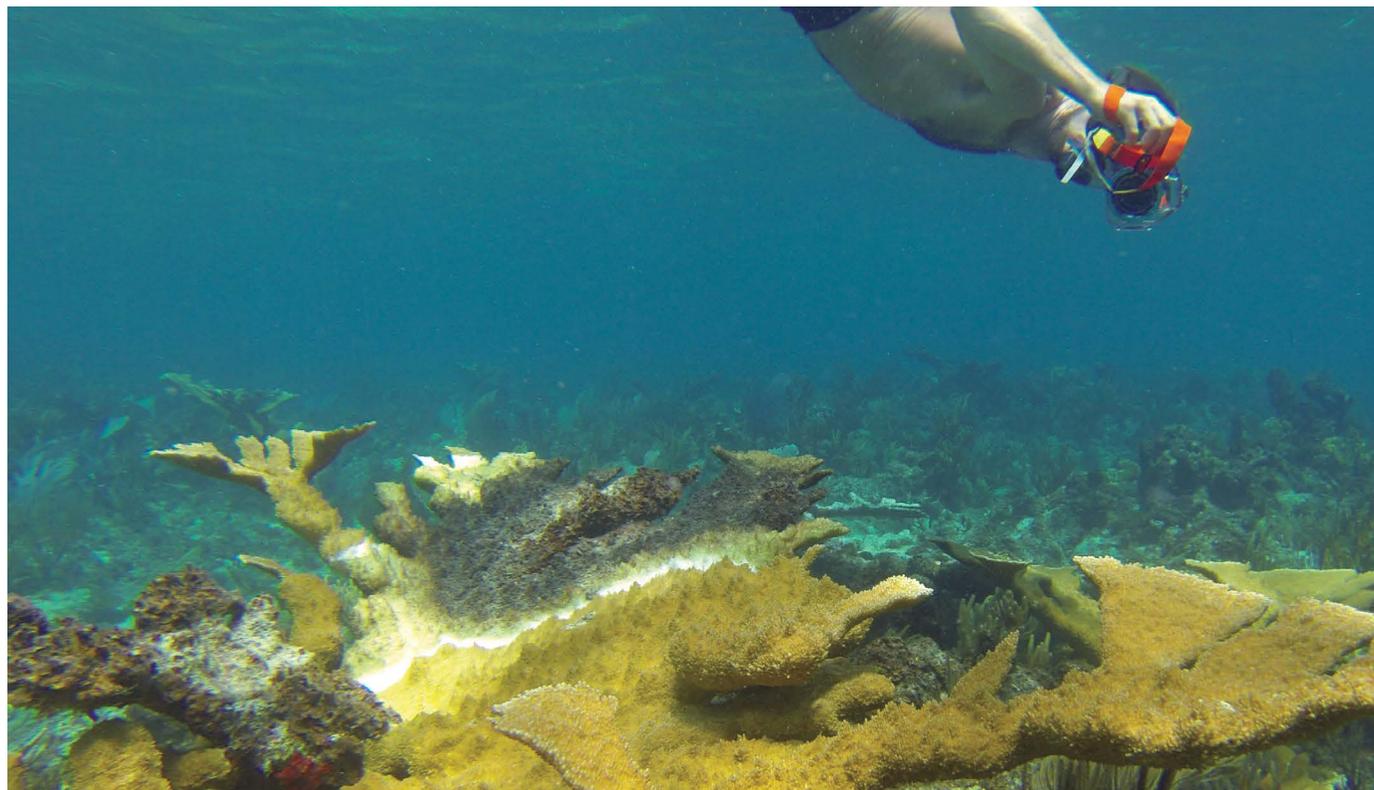
Light is absorbed and scattered as it passes through the atmosphere, water surface, and the water column. This process is influenced by several environmental conditions (e.g., aerosols in the atmosphere, sea surface, or turbidity in the water column), which change over space and time. These changing conditions cause benthic habitats in one location and/or at one depth to look different than the same habitats at a different location (e.g., algae at 5 m water depth will look different than algae at 20 m in satellite imagery). Such variability makes it harder for an algorithm or visual interpreter to discriminate among different habitat types, and hinders the consistent and accurate characterization of aerial photos (Mumby et al. 1998). To reduce these sources of error and to prepare the satellite imagery for the final step of turning 12 different scenes into one seamless mosaic, we performed a number of operations as described below.

Table 3.3. The 12 Worldview-2 scenes were collected between 2011 and 2013.

12/26/2011
9/30/2011
3/11/2012
3/3/2012
9/30/2011
11/18/2011
3/3/2012
11/18/2011
9/30/2011
3/11/2012
8/14/2013
8/6/2013

Table 3.4. The Worldview-2 bands used for this project were: blue, green, red and near infrared 1.

450 - 800 nm
400 - 450 nm
450 - 510 nm
510 - 580 nm
585 - 625 nm
630 - 690 nm
705 - 745 nm
770 - 895 nm
860 - 1,040 nm



Scientist documenting coral reef habitat with Elkhorn Corals in the Arrecifes de la Cordillera Natural Reserve.

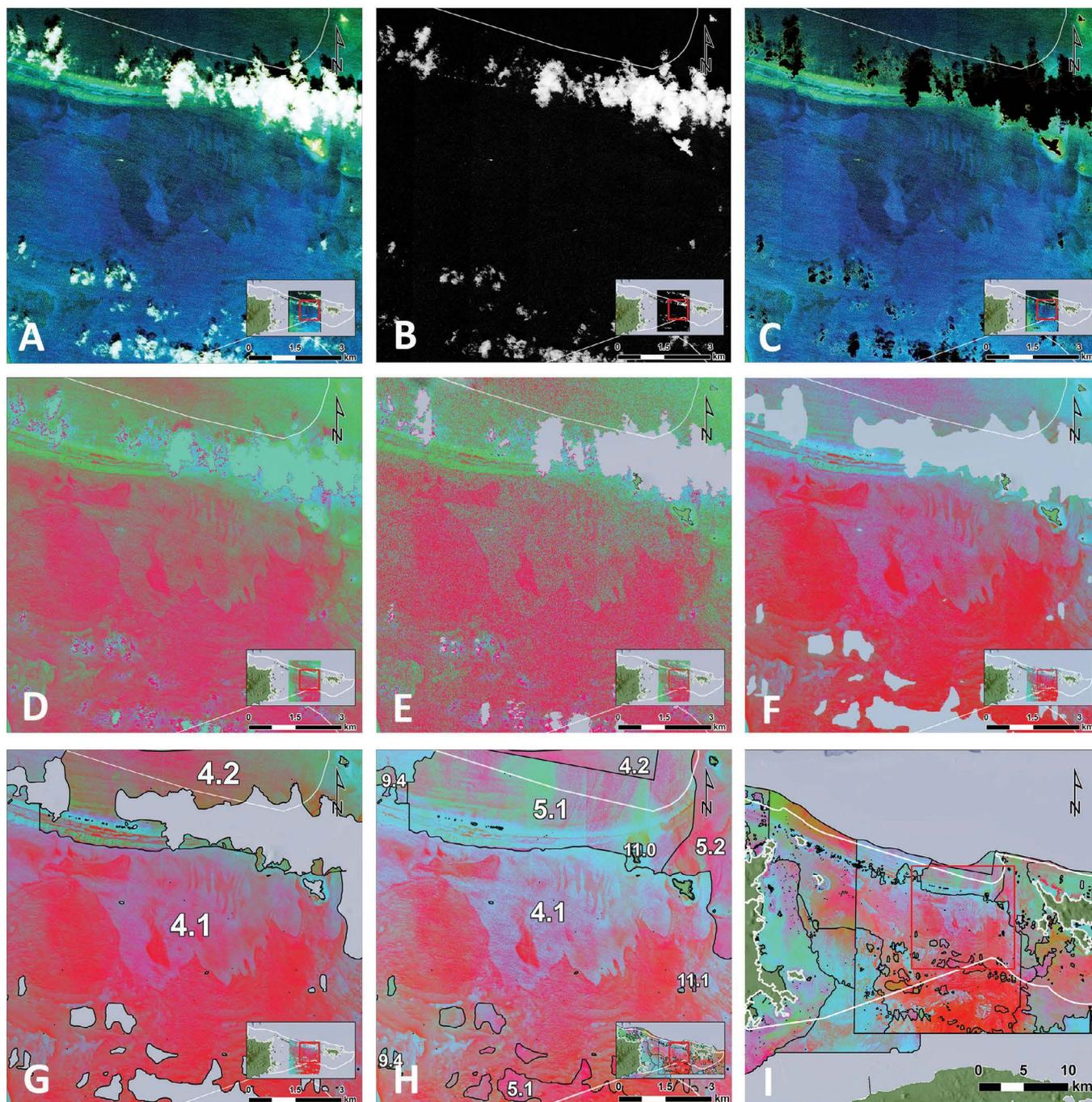


Figure 3.10. The processing of the 12 WV-2 scenes into one mosaic was done in multiple steps. The figure shows part of scene 4 through this workflow (1-6). The process to position and atmospherically correct the scenes was performed prior by Digital Globe. The main steps were: 1. Deglint the original RGB bands (A) using the Near Infrared1 band (B) to produce deglinted RGB bands (C); 2. Water column correction using the Lyzenga method (D); 3. Apply pixel based cloud masking and additional digitized polygon cloud masking (E-F); 4. Despeckle imagery and fill small gaps using a median filter (F); 5. Divide each scene into sub-scenes based on water color and quality changes, the original 12 scenes were divided into a total of 27 sub-scenes ranked based on image quality (G); and 6. Color balance the corrected sub-scenes into one mosaic with highest quality sub-scenes on top (H-I).

Radiometric and water-column corrections

Digital Globe applied atmospheric corrections to all original WorldView-2 scenes using a patent pending technique. All images were converted to surface reflectance using an automatic Digital Globe proprietary method designed for very high spatial resolution panchromatic or visible/near-infrared imagery (Pacifi, 2012). The performance of the approach is discussed in detail in Pacifi, 2013. Sea surface sun glint effects were reduced using the band ratio methodology described by (Hedley, et al., 2005). Each scene was then

corrected for changing water column conditions using the Lyzenga method (Green, et al., 2005; Lyzenga, 1978). The Lyzenga method calculates a correction coefficient by measuring the ratio of attenuation between pairs of spectral bands. To estimate this ratio for each scene, we:

1. Used expert knowledge to locate uncolonized sand habitats at a range of depths (i.e., from 1 to 30 meters)
2. Placed points (n=125) in these locations, where there was little/no sun glint
3. Extracted the red, green and blue band digital numbers at each of these points
4. Converted these red, green and blue digital numbers to their natural log
5. Derived the correction coefficients using Lyzenga's equations for the red and green bands in relation to the blue band, and the blue band in relation to the green band
6. Applied these correction coefficients to each satellite scene using PCI Geomatica

Cloud Masking and Filtering

All scenes were masked to exclude effects caused by clouds, sun glint and wave action (Figure 3.10). The cloud masking was done in three main steps:

1. *Pixel based mask* - A conditional statement written in Python combined four bands (near-infrared, red, green, blue) to identify and classify pixels affected by clouds. As all scenes were different, the masking was done on a scene-by-scene basis.
2. *Buffer mask* - A second mask was created by expanding the pixel based mask with a buffer zone for features larger than 1,000 m². As clouds often have a fuzzy edge this was a way to exclude those edges. The size of the buffer zone depended on the size of the clouds and the properties of the clouds in each area. Some manual edits were done where needed.
3. *Cloud shadow mask* - The edited cloud masks were copied and moved to capture the shadow of each cloud. Additional manual edits were made before the final mask was applied to the imagery.
4. *Filtering*: All scenes were filtered using a 3*3 cell median filter, to remove some of the remaining noise caused by sun glint and wave action and fill in smaller gaps caused by the cloud masks.

Scene ranking

To enable accurate color balancing the original scenes were split into smaller pieces where water and image quality shifted significantly within the scenes. Sediment loads in the water column especially affected the area around Puerto Rico mainland and the sediment plume front was used to split affected scenes. The 12 original scenes were split into 27 images (Figure 3.11). The final images were then compared to each other and ranked based on quality (1-27).

Final water column correction

A final check was done to ensure that the majority of the depth dependence was removed from the final images during the pixel based water-column corrections. Points showing uncolonized sand bottom were extracted from the ground validation data and from visual interpretation of the aerial imagery. The pixel values from each band and each sub-scene were extracted using these points and plotted against depth. A regression curve was fitted to each plot and the regression function was used to correct the affected band using the bathymetry model where significant depth dependence was still found in the imagery. A total of four scenes were found to still have a correlation with depth and were corrected this way.



Cloud cover is one of the main challenges when using satellite imagery.

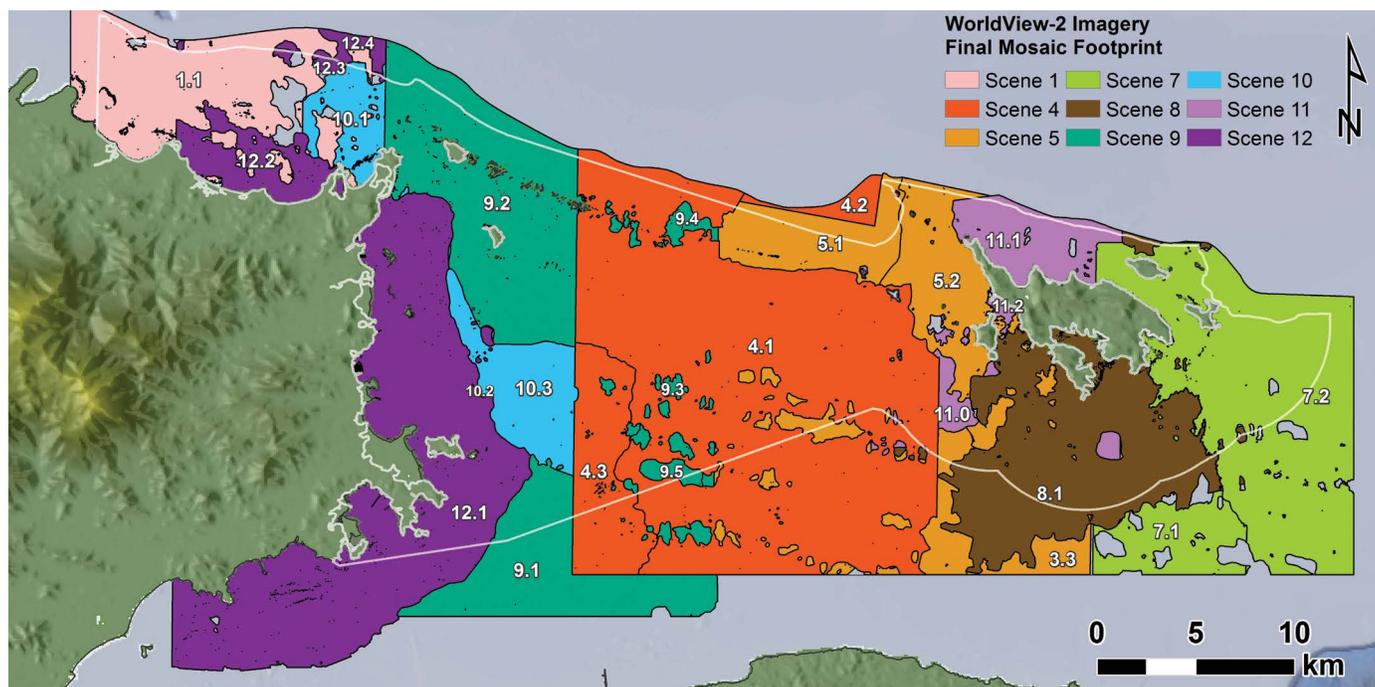


Figure 3.11. Footprints of the 9 WV-2 scenes that build the final color balanced WV-2 mosaic (Figure 3.12). Many scenes were divided into several sub-scenes (25 in total) due to varying data quality within in each scene (for example: scene 10 was divided in 10.1, 10.2, 10.3).

Mosaicking

The corrected images were ranked according to quality (1-27) by visual assessment. PCI Geomatica was used to color balance the 27 images and merge them into one mosaic. The color balancing was done using the neighborhood algorithm in PCI. An image-ranking list was used to place the best images on top. Blending of overlapping images was only allowed at the edges in the mosaicking process to prevent blurring and distortion of visible habitat features (Figure 3.11). The final mosaic had 2 m resolution (Figure 3.12).

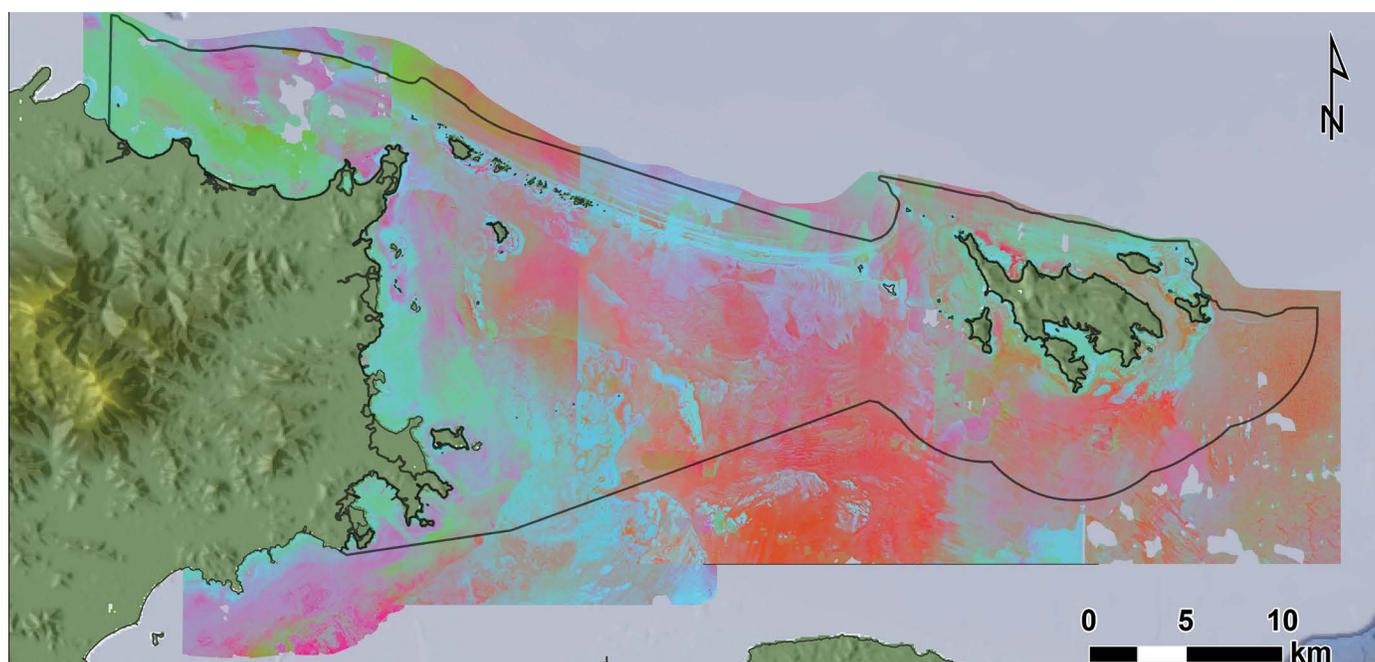


Figure 3.12. The final color balanced and water column corrected Worldview-2 mosaic, containing vital information to delineate and classify benthic habitat features across the whole project area. Figure 3.11 shows the footprint of 25 sub-scenes that was used to create the final mosaic.

3.3.3. Multiband Raster

The PCA image derived from the bathymetric model was combined with the corrected WV-2 satellite mosaic (Figure 3.13). The images were standardized and stacked in the following steps using ArcGIS:

1. Resampled the PCA image from 4 x 4 to 2 x 2 meters using the “Resample” tool.
2. Created a mask by first buffering (expanding) the project area polygon +100 m (to ensure high map quality at project boundary), and then by buffering the shoreline polygons – 4 m to ensure overlap between the *open water* map and the manually digitized *shore complex* map. The modified shoreline was cropped from the modified project area to create the final image mask.
3. Clipped both images (PCA, WV-2) to the mask and set the extent to match the PCA Image pixels using the “Extract by Mask” tool.
4. Stacked both clipped images into a 6-band raster.
5. Replaced all no-data cells in the 6 band raster with the average value of each band for pixels where any of the other bands contained data.

The resulting six band raster combined information from both the bathymetry model and the Worldview-2 satellite imagery. Seafloor habitats were automatically delineated from this 6 band raster using feature extraction algorithms.

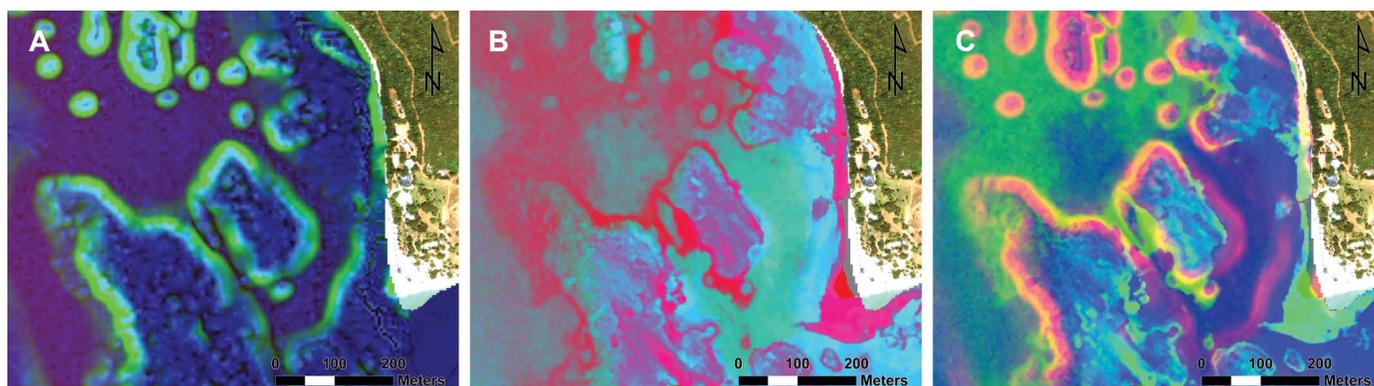


Figure 3.13. (A) 3 band PCA Image, (B) 3 band WV-2 Image, and (C) combined 6 band raster (PCA, WV-2) used for segmentation. The images show reef, sand and seagrass habitats west of Palominos Island, only the WV-2 image (B) contains information to differentiate between seagrass and uncolonized sand, while the PCA image (A) clearly show the reef edges and seafloor topography. Combined into one (C), the two images complement each other.

3.3.4. Habitat Delineation

The *open water* features (all areas outside the shoreline) in the remote sensing imagery were delineated by feature extraction in ENVI followed by additional manual edits.

Automated Segmentation

The marine habitats were delineated using a feature extraction workflow based on the remote sensing imagery. Both depth and satellite imagery were combined in one multiband raster so that the two imagery types could complement each other. For example, when the satellite data was of low quality due to cloud cover or turbid waters, habitat features could often still be extracted from the depth information (Figure 3.13). When both image types were of poor quality the area was categorized as *Unknown*.

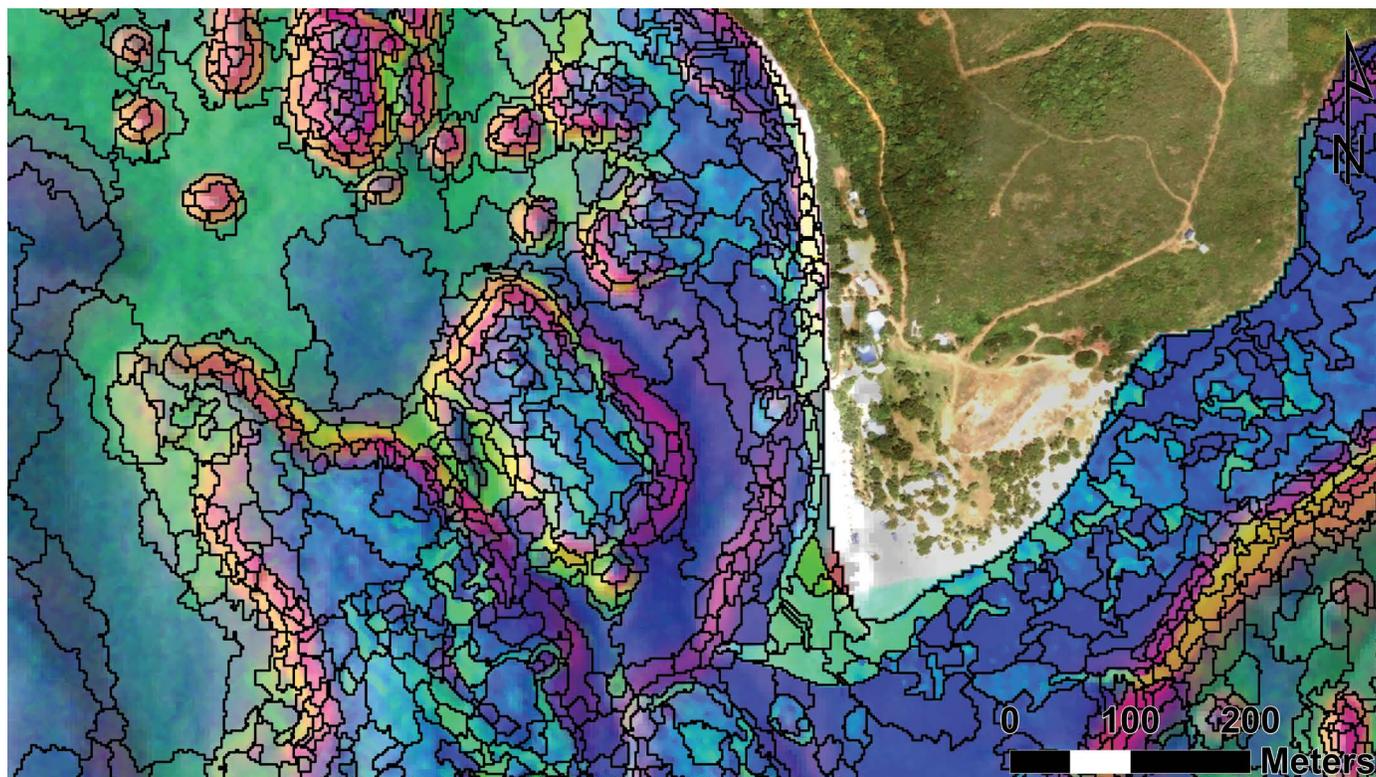


Figure 3.14. Automated habitat delineation using the ENVI Feature Extraction Module applied on a six band image combining WV-2 and PCA (derived from the depth model) bands. The picture shows an area around the south side of Palominos Island with reef, uncolonized sand and seagrass beds.

Feature extraction

Seafloor habitat features were identified and extracted from the multiband raster using the ENVI Feature Extraction (Fx) toolbox (Figure 3.14). This module uses edge detection algorithms to detect and delineate objects in a single image or in a suite of spatially coincident images. ENVI defines an object as a region of interest with unique spatial, spectral (brightness and color), and/or textural characteristics that make it visually distinct from its surroundings (Excelis, 2008). There are three steps involved in extracting discrete objects from an image. Specifically, these steps include:

1. Segmenting the image
2. Merging smaller segments into larger objects
3. Computing spatial, spectral, textual and custom attributes for each object

The first two steps are interactive, allowing the user to adjust the input parameters in such a way that the segmentation captures the features in which they are most interested. In particular, step 1 allows the user to alter the “scale level” of the edge detection algorithm to determine the size of the objects to be extracted. Choosing a higher scale level (>75) causes a lower number of larger segments to be defined, while choosing a lower scale level (<25) causes a greater number of smaller segments to be defined (Excelis, 2008). Step 2 allows the user to alter the “merge level” of the algorithm and to merge smaller segments into larger objects. Choosing a higher merge level (>75) causes segments with faded edges to be merged, while choosing a lower merge level (<25) preserves more of these features with faded edges (Excelis, 2008; Robinson, et al., 2002). In step 3, ENVI computes 14 spatial metrics, 4 textual metrics, 1 band ratio metric, 3 hue, saturation and intensity (HSI) metrics and 4 spectral metrics (for each input band) for each distinct object. These metrics will be referred to hereafter as “Fx attributes,” and are described in more detail in Costa, et al., 2013. The user may then export all of the objects and their associated spatial, textual, HSI, ratio and spectral attributes as a single ESRI shapefile.

Using this workflow, discrete habitat features were identified and delineated in the PCA and satellite imagery.

- Input Raster: WV2 red/green/blue bands and PCA bathymetry
- Segment Algorithm: Edge
- Segment Value: 12
- Merge Algorithm: Full Lambda Schedule
- Merge Value: 82
- Texture Kernel Size: 3

We exported the final habitat features from ENVI Fx as an ESRI shapefile. Each shapefile's attribute table contained 46 Fx attributes describing each segment in the shapefile.

Polygon Aggregation - Minimum mapping unit

The minimum mapping unit (MMU) defines the smallest sized feature that is delineated individually. In order to capture the habitats in high detail, the MMU was set to 100 m² (10*10 meters), which is the same as recent work in the U.S. Virgin Islands (Costa, et al., 2012, 2013). Many segments created in the feature extraction process were smaller than the MMU. In order to aggregate these small segments into larger units with similar spatial characteristics, we developed a new tool in ArcGIS to “eliminate features by attribute” (rather than “eliminate by longest shared border” tool, available with the spatial analyst extension). Using the “eliminate features by attribute” tool, polygons smaller than 100 m² were merged with the surrounding polygon that had the most similar attributes (Figure 3.15). This reduced the total number of polygons from 868,300 to 400,500, while preserving accurate delineations between polygons with different characteristics. Since all polygons were adjusted to comply with the minimum mapping unit before the GV data was classified, the habitat classification model was trained with GV data and polygons true to the minimum mapping unit. This is different than how polygons have been adjusted to the MMU in past mapping efforts (Costa, et al., 2012, 2013) where the MMU was adjusted later in the process (after the model step) by aggregating polygons smaller than the MMU with the neighboring polygon with the longest shared border.

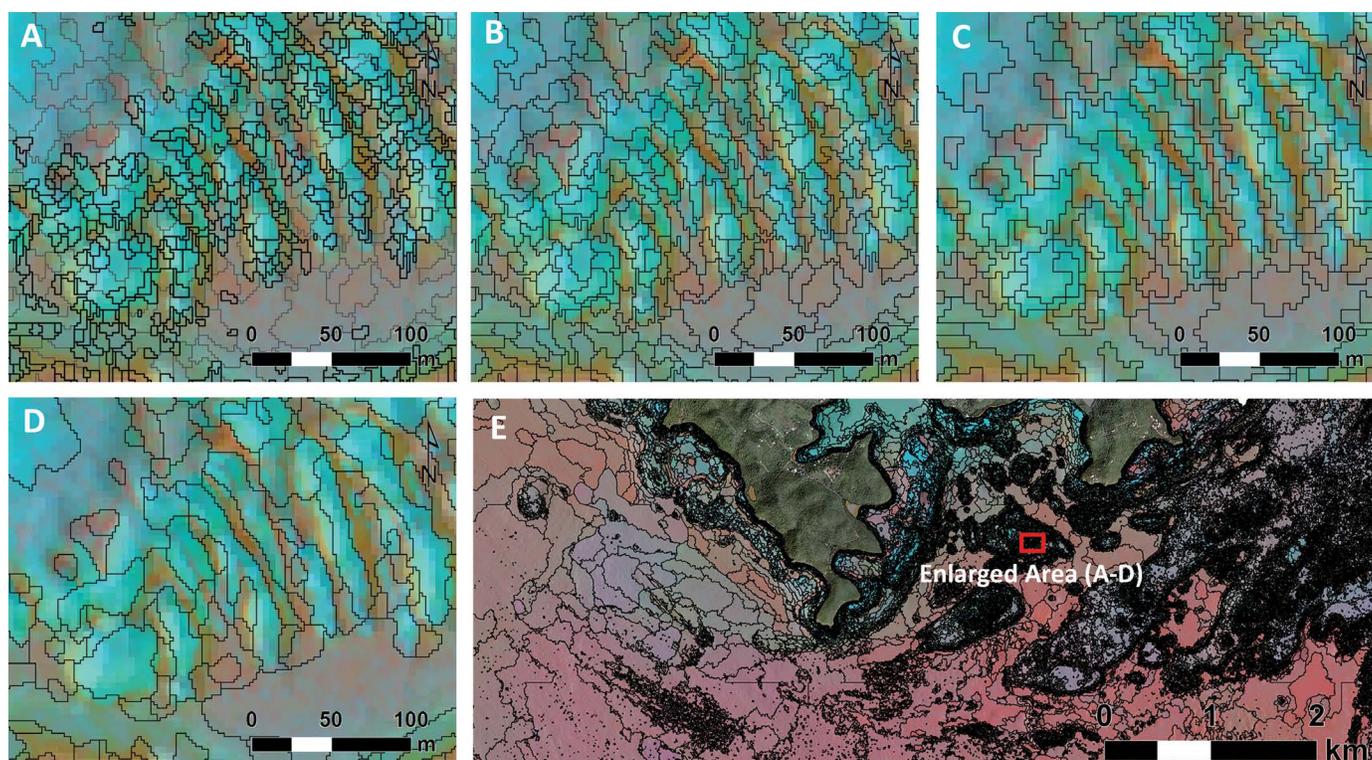


Figure 3.15. This figure shows the main process of aggregating segments from the original output from ENVI (868,300 Segments) to the final habitat map (85,650 Segments): 1. Original Picture A and E (overview) shows the original segments from ENVI feature extraction, (A) has segments smaller than the minimum mapping unit (100 m², or 10*10 m) highlighted in black; 2. The segments smaller than the MMU (100 m²) have been aggregated with the adjacent segment with the most similar spatial signature (B); 3. The classified segments resulting from the habitat models, including predictions for both hard and soft bottom (C); 4. Manually edited and dissolved polygons (D).

3.3.5. Ground Validation

Ground validation (GV) is the process of collecting underwater photos and/or videos at discrete locations in order to improve algorithm performance using the remote sensing data. GV data is needed to create high-quality benthic habitat maps because they help the analyst to visually link (or the algorithm mathematically correlate) habitats on the ground with features visible in the source imagery. Typically, the analyst chooses GV sites using a draft map, developed by digitizing or segmenting habitat features visible in the source imagery (Whitall, et al., 2011; Zitello, et al., 2009).

Field work

Underwater video and photos were collected at 1419 sites across the project area during two field missions (July 8-26, 2013 and October 22- November 8, 2013), recording approximately 40-80 GV sites per day. The field team consisted of two NOAA scientists and a local boat captain. Sites directly accessible by boat were recorded with a drop-camera system and sites not accessible by boat was documented by snorkeling, using a handheld camera and a GPS attached to a buoy. At Flamenco Beach, Culebra, we used a two-man kayak to navigate the shallow reefs, then recorded our GV data by snorkeling or by holding a camera underwater directly below the kayak (Figure 3.16).



Figure 3.16. A variety of small vessels were used to collect ground validation data in the mapping area to adjust to the local conditions of the area surveyed, including kayaks (left), a DRNA vessel on Culebra (middle), and a local fisherman who contributed his skills to navigate shallow reef areas (right).

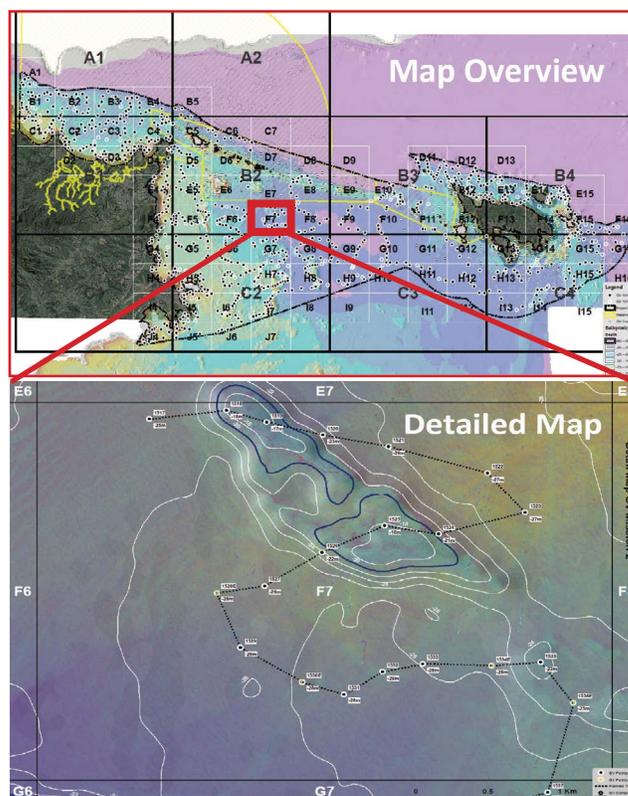
Site selection

The GV sites were planned by manually placing points on a draft habitat map. The sites were selected to include all types of remote sensing signatures that could be identified, covering habitat features across the whole project area (approximately two GV sites/km²). The GV sites were placed along track lines to minimize travel distance/time and fuel consumption (Figure 3.17).

Video transects

Each video was recorded to capture both a downward view (camera perpendicular to the sea floor) and a landscape view of the seafloor approximately 0.5 -1 m above the bottom. The downward view helped estimate percent cover of hard bottom, corals and biological cover. The

Figure 3.17. The GV sites were placed along pre-planned track lines to help minimize travel time while visiting as many unique habitat locations as possible across the whole survey area (1,419 sites in total). Ninety-two printed detailed field sheets (3x4 km each), in combination with pre-loaded Garmin GPS points and a Panasonic Toughbook running ArcGIS, helped the field team navigate to the GV sites.



landscape view allowed for the capture of larger structures and habitats, and helped to make additional observations such as the presence of ESA-listed corals and fish.

Drop-camera survey

Sites accessible directly by boat were surveyed with a drop-camera system. The setup had two cameras: a SeaViewer Sea-Drop 950 camera and a GoPro Hero 3 Black Edition camera mounted on top of the SeaViewer camera. The SeaViewer camera had two red lasers positioned in parallel 13 cm apart (Figure 3.18). The low resolution (VGA) SeaViewer video was viewed and recorded in real time on a Panasonic Toughbook laptop, which also displayed an ArcGIS window showing our location on the draft habitat map using the Toughbook internal GPS. The Toughbook setup allowed us to control the camera and make sure that we were in the correct position. The GoPro camera simultaneously recorded HD video (1440*1920 pixels) and 12 MP photos 1 photo per 5 seconds directly to a 64 gb internal memory card. The GoPro camera was also used to record the location of the GV transects through a calibrated timestamp in each photo in combination with the recorded GPS information (see “GoPro Setup” and “Photo Positioning” below).

Each drop-camera site was filmed for approximately 1-3 minutes, depending on habitat complexity. The boat was left drifting with the prevailing current and wind during the drop-camera survey to also capture the transition to adjacent habitats.

The habitat field observations were recorded onboard the vessel using a Trimble Geo XT GPS data dictionary, pre-programmed with the habitat classification scheme. The camera position was recorded using the same Trimble GPS receiver, located approximately 2.5 meters from the start of the drop-camera cable. The total distance between the GPS and the camera varied depending on depth, wind, and currents, by approximately 0-15 meters. The habitat information and location of each transect was recorded directly in the Trimble GPS before moving on to the next site using a pre-loaded data dictionary containing the classification scheme. The Trimble GPS also recorded the position every 2 seconds, capturing the full GPS trackline of each field day.



Figure 3.18. (Left) The habitat analyst with field setup: a Toughbook showing live video feed from the drop-camera, and a Trimble GPS to record location and habitat information. (Middle) Drop-camera system under water, the rope and the cable helped the field team to maneuver the camera system to capture both landscape and downward views of the seafloor. (Right) The SeaViewer camera with a GoPro camera mounted on top of the SeaViewer camera, and two lasers positioned in parallel 13 cm apart.

Snorkel setup

Snorkel surveys were used for sites that were too shallow or too close to shore to access by boat. The Snorkel GV setup consisted of a GoPro camera on a small frame together with two lasers mounted in parallel 10 cm apart for distance reference, and a dive safety buoy with a Garmin 78 GPS unit (recording the GPS position every 2 seconds) attached to the snorkeler with a 5 meter floating rope and a quick release belt (Figure: 3.19). For deeper dives a dive reel was used to extend the rope to the safety buoy. The snorkel sites took approximately 5-10 minutes and generally involved multiple video transects as the snorkeler also documented the habitats encountered during the swim to and from the preplanned site. The snorkel sites were classified in the field, and the habitat information was entered into the Trimble once back on the boat. The snorkel videos were positioned after the fieldwork, using the Garmin GPS information and the GoPro camera time stamp (see *post processing below*).

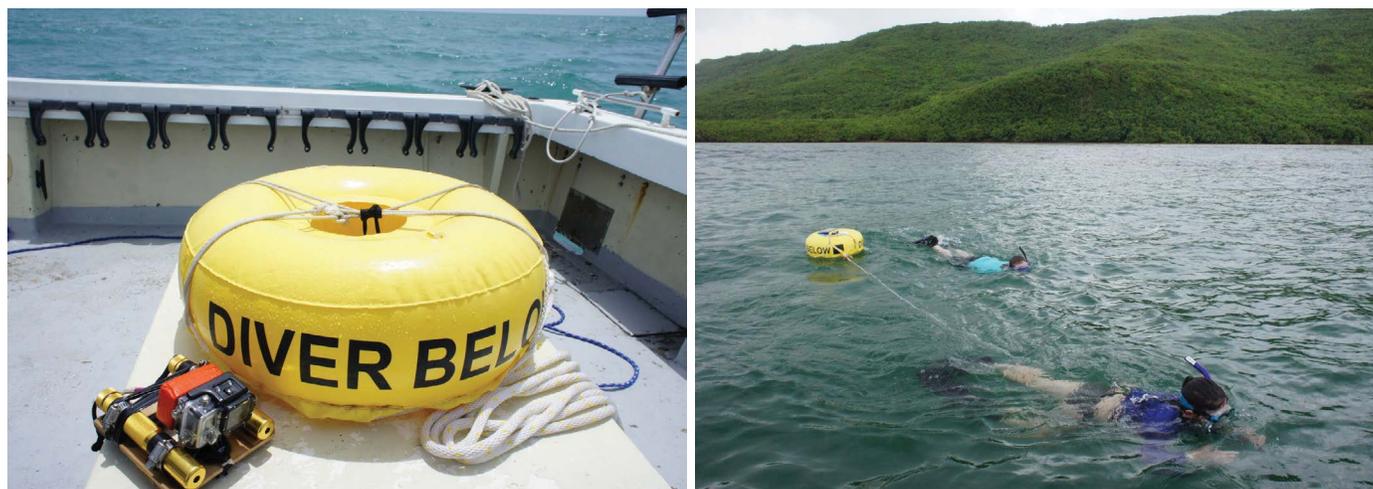


Figure 3.19. (Left) Snorkel setup: A time calibrated GoPro camera with 2 lasers mounted in parallel 10 cm apart, and a snorkel safety buoy with a Garmin GPS recording the position every 2 seconds. (Right) A snorkel team recording a GV transects.

GoPro setup and calibration

The GoPro Hero 3 Black Edition cameras were set to record video with 1,440*1,920 pixel resolutions at 24 frames per second, and to simultaneously recorded one 12 MP photo every 5 seconds. The GoPro's were encased in the standard 60 meter water proof housing with a flat port to ensure sharp underwater videos. Each camera used a 64 gb microSD card to record the data.

Accurate internal time is a key to positioning the GV footage, which, in turn is a requirement for connecting the GV data with the remote sensing imagery to create a high resolution habitat map. The GoPro Android Application was used to set the internal camera time to network time at the very start of each field mission. To monitor the internal camera time (the internal clock drifts slightly over time, time drift may vary between cameras), we recorded a video showing a screen with exact time (<http://www.timeanddate.com/worldclock>) every 3 days during the field missions and used this information to correct the time drift after the field mission.

Daily backup

All videos, photos, and GPS information were backed up on a daily basis on two mirrored external hard drives. The downloaded Trimble and Garmin data were added to the Toughbook ArcGIS mxd, which allowed us to keep track of all logged sites in the field.

GPS reference points

We recorded a number of GPS points using two Trimble GeoXT GPS receivers to control the positioning of the satellite and aerial imagery. We identified distinct features in the imagery, like the corner of a dock, and then recorded a GPS fix point.

Post-Processing

The time calibrated GoPro videos (>1,400) and photos (>30,000) together with the GPS log enabled us to position the GV data accurately, even if the field team had mixed up a site name or the location of a transect. This was important to keep track of the large amount of GV sites in this mapping project.

GPS data

The Trimble GPS data was differentially corrected using Trimble Pathfinder Office software and Continually Operating Reference System stations (The CORS station used were CUPR, PRLP and ZSU1). We extracted and post processed the full GPS track log, as well as the recorded transects and the associated average position of each site that was recorded in the field using the Trimble device. The Garmin 78 GPS data was downloaded from the field unit using the DNR GPS software. The processed Garmin and Trimble positions were exported as point shape files.

Photo and video transect positioning

We extracted the timestamp for each GoPro photo (1 photo/5 seconds of video) and connected it with the timestamp on the GPS device that was used to log each transect. We calibrated and adjusted the photo time stamp to ensure a match between GPS time and photo time using the following steps:

1. Calculating the time drift: We fit a linear regression curve to the internal time calibration recordings (the difference between internal camera time and the correct network time) which averaged 3-4 seconds per 24 hours (the two GoPro cameras used had slightly different time drift).
2. Renaming the photos: All photos showing the seafloor (excluding blue water and on board shots) were batch renamed in Adobe Bridge CS6 using the embedded timestamp to yymmdd_hhmmss. Snorkel and drop-camera photos were kept separated and a list with all photo file names was extracted for each folder.
3. Connecting photos with position: We used Excel to calculate the corrected time for each photo (using the calibration curve from step 1), and then paired the corrected time with the closest matching GPS time record. The resulting table included the photo name, the position, the corrected time, the GPS time and the time difference between corrected photo time and GPS time. The time difference was used to identify and exclude photos with missing GPS records.
4. Connecting photos in ArcGIS: We imported the table from step 3 into ArcGIS and created a geo-positioned point shapefile. The photo name for each point was connected with the correct photo using an HTML Script (Figure 3.20).
5. Creating video transects: We used the point shapefile from step 4 in ArcGIS to create a line shapefile for each video transect (separated using the timestamps), then did a “join by location” to extract the corresponding video name using the site information recorded with the Trimble GPS in the field.

Video processing

The videos were re-named to the video ID recorded during field work using the site name displayed on a plack or recorded by voice at the start of each video. We controlled each video name by comparing with the name and timestamp on the corresponding Trimble GPS point. We then cropped and compressed the videos using Squeeze 9 to prepare the videos for streaming through our web based BioMapper portal.

Ground Validation data classification

The underwater footage, together with the feature extracted habitat segments (MMU 100 m²) and the remote sensing imagery, was used to generate a final set of classified GV data points. Multiple GV points were extracted for any video transect that intersected several habitats. Comparison between the videos and the remote sensing data was used for quality control and to adjust any remaining position problems. In total 1,419 videos resulted in 2,471 classified GV points. The high quality HD video and photos allowed us to extract additional ecological information (ESA listed coral species, fauna and fish information and co-occurring biological benthic cover). We used a domain database with subclasses to create a drop-down menu interface with the habitat classification scheme (Figure 3.20). This setup helped us reduce errors associated with manual attribute edits and saved time in the GV classification process.

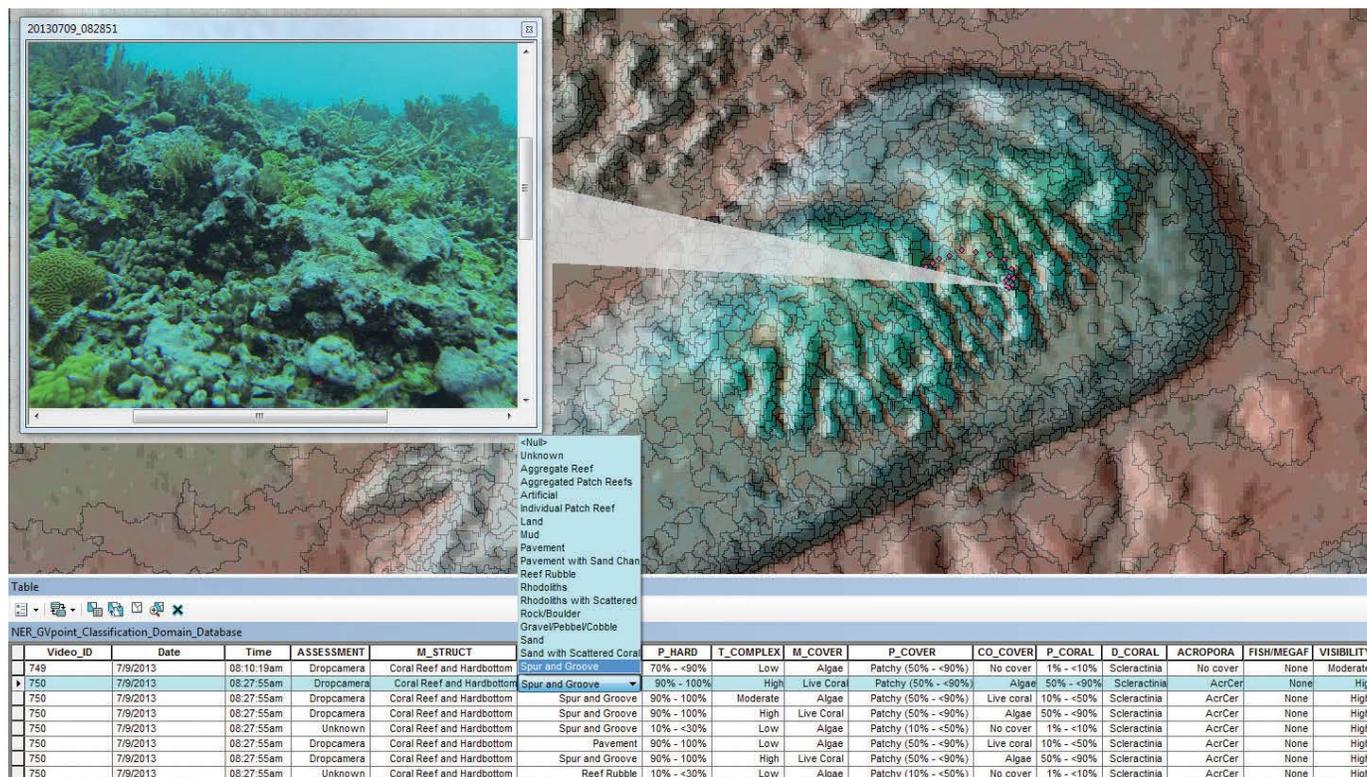


Figure 3.20. The underwater video field data was analyzed together with remote sensing imagery (bathymetry, satellite imagery and aerial photos) and the habitat segments to create the final GV data set. A domain database was used to create a drop-down menu interface with the habitat classification scheme in ArcGIS. This setup reduced errors associated with manual attribute edits, and saved time in the GV classification process. It also provided a way to quickly add additional observations like ESA listed corals and fauna observations.

3.3.6. Habitat Modelling

In order to classify the habitat polygons (derived from feature extraction in ENVI) in the first draft habitat map, we developed a number of statistical models from the information derived from the GV data, the habitat polygons and a suite of spatial predictors. These models were then applied to the habitat polygons to develop the map. Previous habitat mapping efforts by the NCCOS Biogeography Branch in nearby USVI have successfully used the well-established decision tree technique QUEST (Costa, et al., 2009; Costa, et al., 2012) to classify habitat maps, as well as the more complex ensemble modelling technique, Random Forest (Costa, et al., 2013). Though successful in terms of final map accuracy, these projects have involved a substantial amount of manual editing (up to 90% of all polygons were edited). Considering time available and the complexity and size of the project area (over 400,000 habitat polygons waiting to be classified), manual editing could not be done for the same proportion of polygons as previous mapping efforts (34% of the polygons were manually edited, Table 3.6). We therefore explored and implemented Boosted Regression Tree (BRT) modelling in R, together with a suite of spatial predictors, to improve the model accuracy and reduce the need for manual edits (see Table 5.4 (pg. 102) for a comparison of model accuracies versus the manually edited map accuracies). BRT is an advanced machine learning technique that uses boosting to produce a prediction model from a large number of simple classification trees and has only recently been used for ecological modeling (Elith and Leathwick, 2014; Elith, et al., 2008). To optimize and ensure the quality of our habitat models, we evaluated the results by cross validation in R and through accuracy assessment using a subset of the GV data (30% of the GV data was set aside for accuracy assessments in the initial models), and finally through visual evaluation by an expert habitat mapping analyst.

Predictors

We developed a number of spatial predictors that were relevant to the distribution of the habitat classes. We used zonal statistics in ArcGIS to update each habitat polygon with statistics from the predictor layers (including statistics with mean, median, standard deviation, maximum, and minimum values for the spatial predictor layers in each polygon), and then intersected the habitat polygons with the GV data to add the

polygon statistics to each GV data point. In addition to predictors developed from the bathymetry model, the satellite imagery, and the shape of the habitat polygons, we also used the shoreline to produce distance to shore layers, and high resolution wave and ocean current climatology products from the CariCOOS Near-shore Wave Model (Canals, in press). Figure 3.21 shows examples of the predictor layers, and Table 3.5 lists all the predictors that were used for the final models.

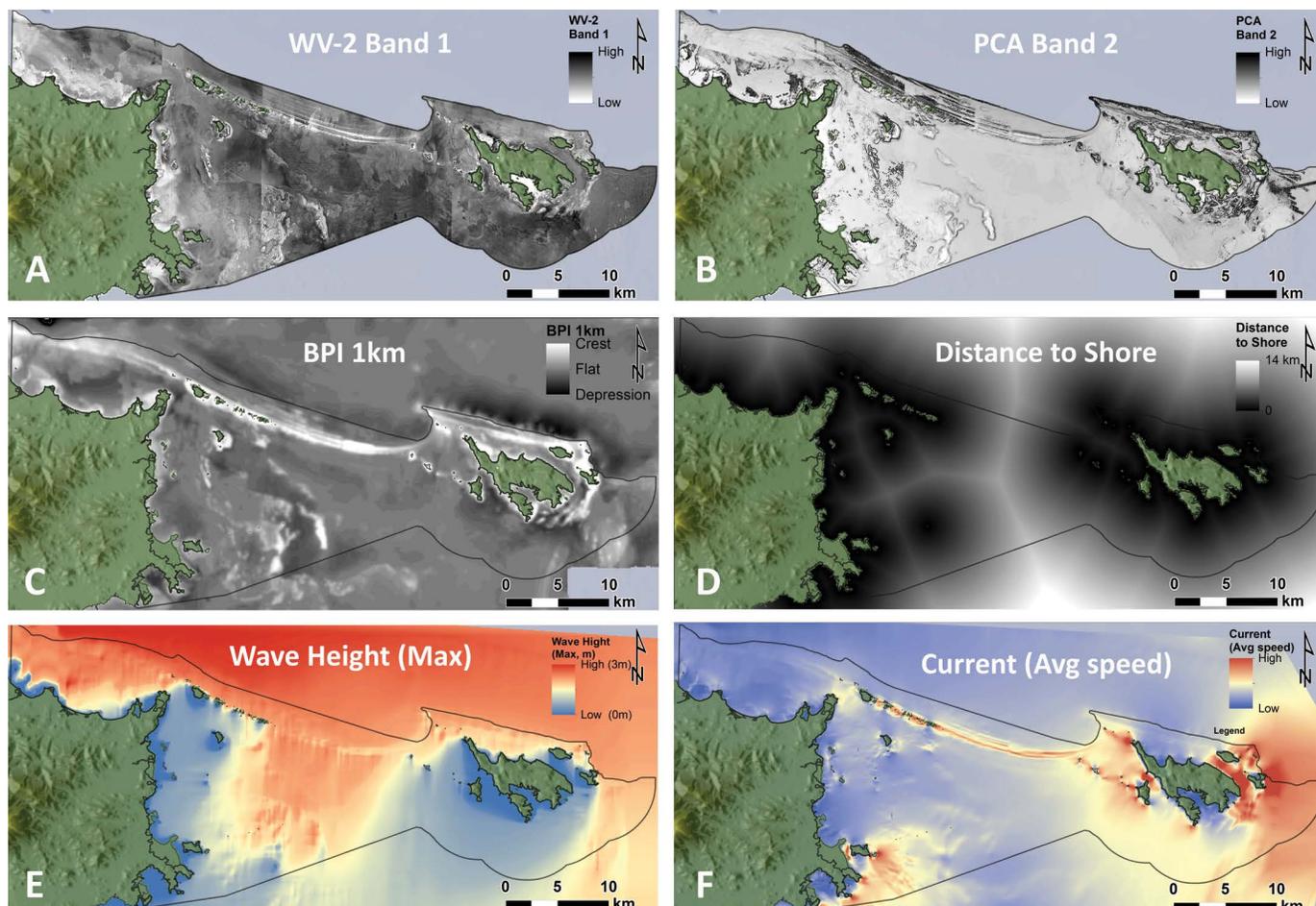


Figure 3.21. The figure shows a few examples of predictors that were developed and combined with the habitat segments and GV data to predict the benthic habitats using Boosted Regression Tree models: (A) Worldview-2 Imagery Band 1 (out of 3); (B) Principal Component Analysis Imagery (based on the depth model) Band 2 (out of 3); (C) 1 km scale Benthic Positioning Index (BPI) developed from the depth model, capturing large scale features of the seafloor (such as crests, flats and depressions); (D) Distance to shore developed using the mapped shoreline; (E) Wave height model (maximum wave height August 2013 - January 2014) developed by UPRM and CariCOOS; (F) Current model (average current August 2013 - January 2014) developed by UPRM and CariCOOS. See Table 3.5 for a full list of the 26 predictors used in the final models.

Modeling

Several multinomial Boosted Regression Tree models were developed in R v2.15 using the Caret package (Kuhn, 2008) to implement Ridgeways 'gbm' package for Generalized Boosted Regression Models (Ridgeway, 2013). The developed models were applied spatially using 4 m raster versions of the predictor layers. Initially, model performance was tested with a subset of GV data, intersected with all of the 88 available predictors from the habitat polygons. Model test runs showed that when the number of predictors was reduced from 88 to 26, the model performance improved, while processing time was greatly reduced. We optimized model parameters using cross-validation and the `expand.grid` function in the Caret package. During the model development stage, we partitioned 70% of the GV data to train the model, and 30% of the GV data to validate the model predictions. We also validated the model result visually in ArcGIS to control for spatial autocorrelation and over fitting. For the final habitat models, we used 100% of the data to train the models. An independent accuracy assessment was used to estimate the final map accuracy (see Chapter 4).

The final parameters used (same for all 6 models) were:

- Algorithm: Generalized Boosted Regression (gbm)
- Number of predictors: 26
- Number of trees: 1,000
- Interaction depth: 10
- Shrinkage (learning rate): 0.005

Table 3.5. The table lists the 26 predictor variables used in the final 6 habitat classification models, and shows how the predictor variables contributed to each model (percent total contribution of each predictor/model). The table also shows the number of classes predicted in each model and the number of GV data point used to train the models.

PREDICTOR VARIABLES AND MODELS		All GV Data Detailed Structure	Hardbottom GV				Softbottom GV	Summary
		13 classes 2,545 samples	% Hardbottom 5 classes 1,663 samples	Topographic Complexity 5 classes 1,705 samples	Biological Cover, % Cover 10 classes 1,662 samples	% Coral Cover, Detailed Coral Cover 10 classes 1,654 samples	Biological Cover, % Cover Soft 9 classes 881 samples	
Predictor Layer	Polygon Statistics	% Contribution	% Contribution	% Contribution	% Contribution	% Contribution	% Contribution	% Contribution
Y	Centroid	4.6	8.7	2.6	23.4	11.1	9.5	10.0
WV-2 Band 3	Mean	7.3	20.5	2.8	8.2	2.8	16.4	9.6
PCA Band 1	Mean	4.3	3.8	5.4	15.3	10.2	11.3	8.4
PCA Band 3	Mean	7.7	11.9	6.8	3.5	2.2	3.5	5.9
Slope Direction (300m Bathy)	Median	4.0	5.9	6.0	3.7	4.4	7.4	5.2
Wave Height Max	Mean	8.0	7.7	5.6	2.8	3.2	2.9	5.0
X	Centroid	5.2	3.9	2.8	1.9	8.3	3.5	4.3
Current Average	Mean	2.7	2.6	2.3	9.2	4.6	3.3	4.1
PCA Band 2	Mean	3.4	2.7	9.1	2.4	2.6	2.8	3.8
PCA Band 1	Minimum	2.9	1.8	5.2	2.2	4.4	4.7	3.5
PCA Band 3	TX Variance (ENVI)	3.9	1.1	12.5	1.1	1.8	0.8	3.5
FX_AREA	Sum	5.7	1.8	6.1	1.3	1.3	3.0	3.2
Current Maximum	Mean	1.5	1.8	2.2	3.2	7.1	3.5	3.2
Euclidian Distance to Puerto Rico	Mean	5.3	2.1	3.0	1.2	6.2	1.4	3.2
PCA Band 2	TX Range (ENVI)	3.1	2.1	4.3	1.7	1.3	4.5	2.8
Benthic Positioning Index, 100 m	Median	9.1	1.5	1.5	1.7	2.6	0.6	2.8
WV-2 Band 1	Mean	2.9	3.7	2.1	2.9	2.0	3.2	2.8
Wave Height Average	Mean	1.9	3.0	3.3	2.5	2.5	2.7	2.7
PCA Band 3	TX Range (ENVI)	4.6	1.4	4.3	1.2	2.0	2.3	2.6
Euclidian Distance to Shoreline (MMU 200,000 m ²)	Mean	1.2	1.4	3.1	1.8	6.2	2.1	2.6
Euclidian Distance to Shoreline (MMU 100 m ²)	Mean	3.9	2.3	2.0	1.8	3.1	1.8	2.5
Euclidian Distance to Culebra	Median	2.1	2.5	2.0	1.2	4.0	1.7	2.3
WV-2 Band 2	Mean	1.8	2.9	1.6	2.7	1.9	2.5	2.2
Euclidian Distance to Shoreline (MMU 10,000 m ²)	Mean	0.9	1.0	1.8	1.2	2.2	2.5	1.6
Benthic Positioning Index, 1 km	Median	1.7	1.5	1.2	1.7	1.6	1.8	1.6
Slope of Slope (300 m model)	Mean	0.3	0.6	0.5	0.4	0.3	0.5	0.4

In order to predict the full thematic resolution of our habitat classification scheme, we divided the habitat attributes into several different models. This reduced the number of class combinations each model predicted (outputs with over 100 possible combinations was impractical to predict due to computation speed and memory limits). We split the GV data into hardbottom data and softbottom data and made separate predictive models for those two categories. We then predicted “geomorphological structure” (which includes both hardbottom and softbottom classes) from the whole data set and combined the modelling results. Once manual quality checking and editing was completed, we used the hard/soft bottom information in the geomorphological structure class to create the final habitat map Figure 3.22. We converted our final six habitat prediction models to shapefiles using ArcGIS’s “Raster to Polygon” tool and combined them into one shapefile using the Union tool.

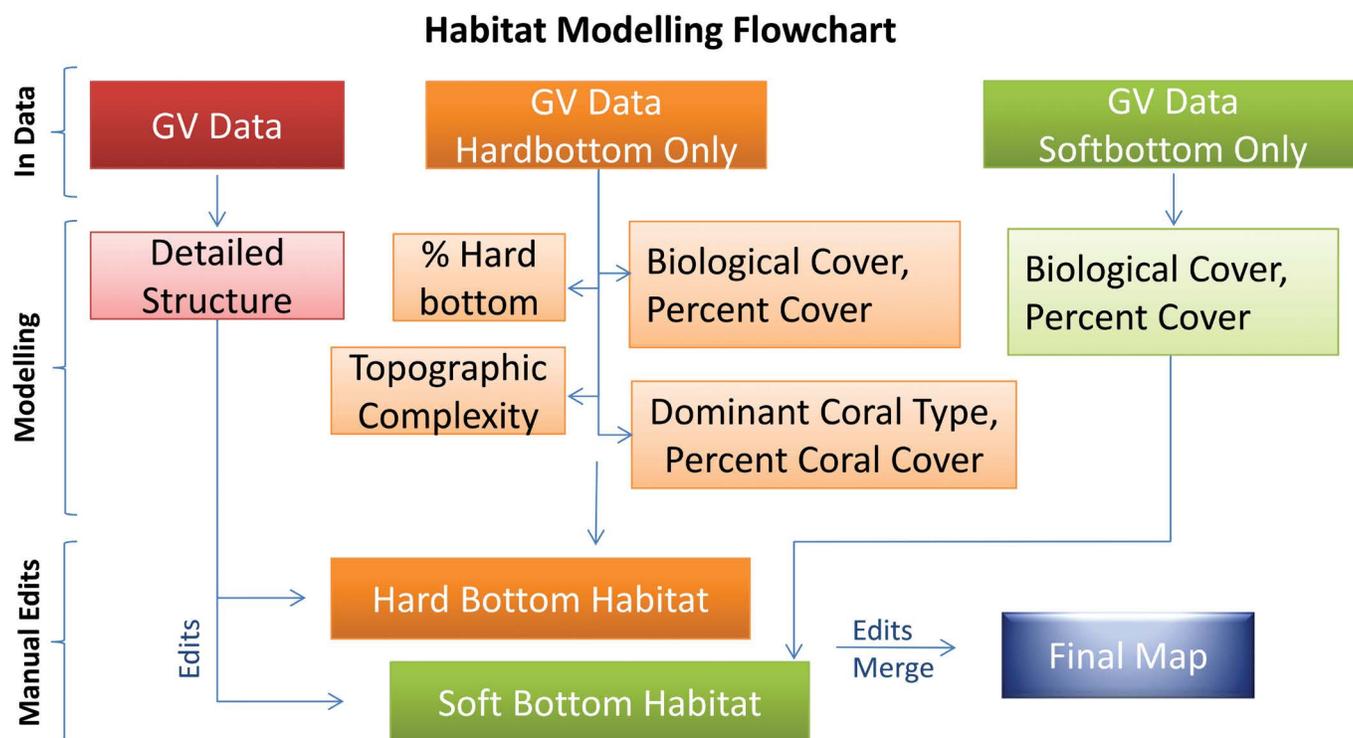


Figure 3.22. The flowchart illustrates the 6 different models that were used to predict the habitat classes. Every box in the modelling step (middle) represents one combined model. We first modelled *detailed geomorphological structure* using all GV data. Second we divided up the GV data into two data sets, (by hard and softbottom), then predicted all other parts of the classification scheme separately for hard and softbottom. Once the manual edits had been completed to improve the hard versus softbottom prediction derived from the detailed geomorphological structure model, we used this information to determine the final model prediction for each habitat attribute.

3.3.7. Manual Classification

Manual edits of the habitat models

The classified map, developed from the Boosted Regression Tree models in R, was quality controlled and manually edited in ArcGIS (see Table 3.6 for estimated numbers of edited polygons). The map shapefile was ingested into a domain geodatabase with subclasses (same domain used for the classification of the GV data). The subclasses translated the integer values from the model to text descriptions of each habitat type and allowed drop-down menu editing of the habitat polygon attributes, speeding up the manual classification process. The model outputs included predictions for both a hardbottom and a softbottom alternative for each habitat polygon and attribute. Therefore, the first priority for the manual edits was to make sure that the hard and softbottom predictions were correct. Certain hard/soft bottom classes were easily mixed up since they had similar remote sensing signatures. For example: flat pavement with a thin sand layer was confused with sand with algae, deep seagrass beds were confused with flat pavement dominated by soft corals, and low density reef rubble with seagrass was confused with sand with seagrass. In addition to methodic visual

evaluation of all areas at multiple zoom levels, we used advanced selection techniques based on habitat attributes, neighboring polygons, and polygon area to identify groups of polygons that needed special attention (for example to identify remote sensing data artifacts that had been confused with small patch reefs).

Polygon re-delineation was done at scale 1:1,000 in regions with moderate-high quality data (bathymetry and or WV2 Imagery), and at scale level 1:2,000 in regions with poor quality/low resolution data. As an extra control, all habitats in shallow water close to the shoreline were controlled and corrected using available high resolution aerial imagery (2007, 2010). Once all edits were made we used the hard/soft bottom information in the geomorphological structure class to determine the final attribute for percent hardbottom, topographic complexity, biological coverage and coral cover. We used the “Dissolve tool” in ArcGIS to join all neighboring polygons with the same final attributes, changing the final number of habitat polygons from 167,500 to 94,800 (Figure 3.23 provides an overview of the segment merging operations used).

Table 3.6. Estimated number of polygons that were manually reattributed because they were deleted, added and/or reclassified. These numbers are based on three iterations of randomly distributed points (n=3,000) stratified by detailed structure type and weighted by area. Habitat classifications contained in the original map (i.e., the unedited map produced by the BRT models) and the final map (i.e., the map that was manually edited) were extracted at each of these points, and compared to determine whether they had been changed.

	4.4%	3.1% - 5.7%
	15.5%	12.4% - 18.6%
	6.6%	5.3% - 7.9%
	9.7%	8% - 11.4%
	10.7%	9.7% - 11.7%
	16.5%	13.7% - 19.3%
	8.7%	6.1% - 11.3%
	8.1%	6.4% - 9.8%
	34.3%	36.7% - 31.9%

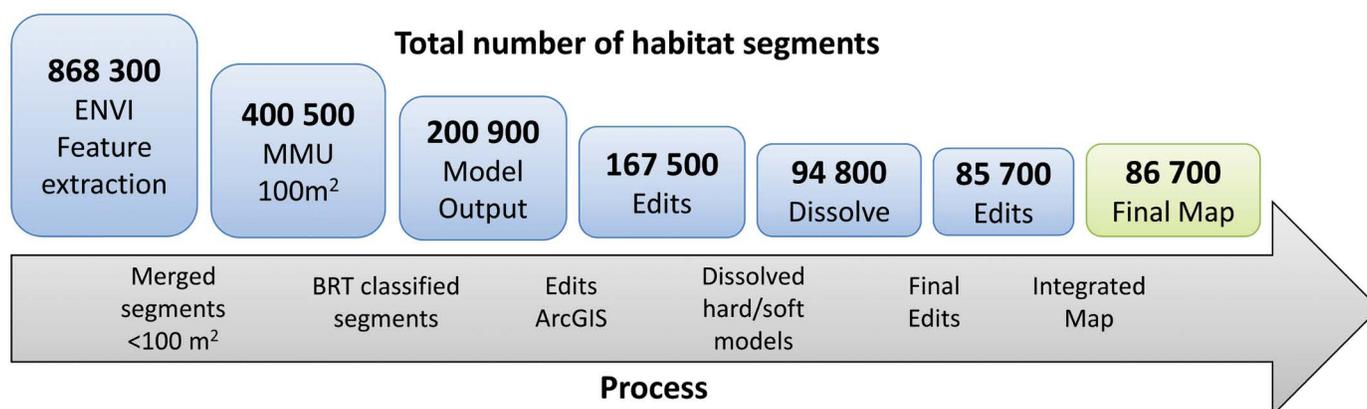


Figure 3.23. The figure shows how the total amount of habitat segments change through the habitat classification process, from the original 868,300 segments derived from the feature extraction process to the final map with 86,700 segments. See Figure 3.15 for a graphical representation of a section of the map through the same process.

In a final step, the edited polygons were smoothed using a series of operations: (1) the polygons were smoothed using the ArcGIS “Smooth Polygon Tool” (PEAK Algorithm, tolerance = 10 meter), (2) the polygons were converted to a 2 m resolution raster using the Raster to Polygon tool, (3) a majority filter was applied, and (4) the rasters were then converted back to polygons (the pixelated appearance drastically reduced the polygon file size and increased the drawing speed).

3.4. FINAL MAP INTEGRATION AND EDITS

We integrated the *Shore Complex Map* (3.24a) with the *Open Water Map* (3.24b) in five steps:

1. Merged a copy of the *Shore Complex Map* into one polygon, and then clipped it to the *Open Water Map* to delete any overlapping polygons (the *Open Water Map* had purposefully been buffered 4 meters across the shoreline to ensure sufficient overlap, see section 3.3.2).
2. Combined the *Shore Complex Map* and the cropped *Open Water Map* into one map.
3. Identified small gaps and slivers in the combined map by merging a copy of the map into one polygon, then extracting any remaining gaps by clipping the merged map polygon to a larger polygon. Any small gap found was extracted and combined with the map from step 2.

4. The gap polygons were then merged with the *Open Water* Polygons in the joined map using ArcGIS's "Eliminate" function (this function merges selected polygons (our gap polygons) with the neighboring polygon with the longest border).
5. Manual quality control and final edits of the combined map.

Once the draft integrated map draft was completed, the habitat map was translated from integer values (integer values were used to code the habitat map in the geodatabase) to text based descriptions using join to table. The translated draft habitat map was exported as a shapefile. The draft map was then evaluated by an independent accuracy assessment team (see Chapter 4). Once the map accuracy assessment had been completed, we updated the draft map based on the additional habitat information from the accuracy assessment to increase the final map accuracy.

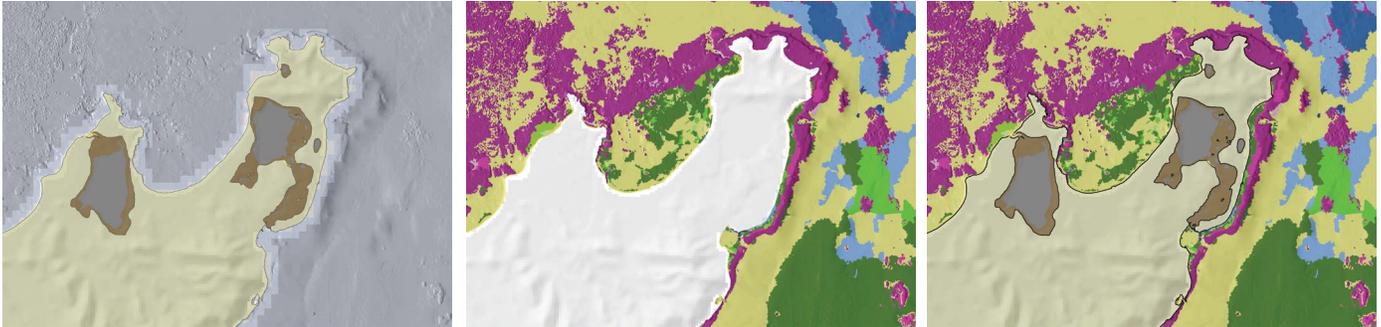
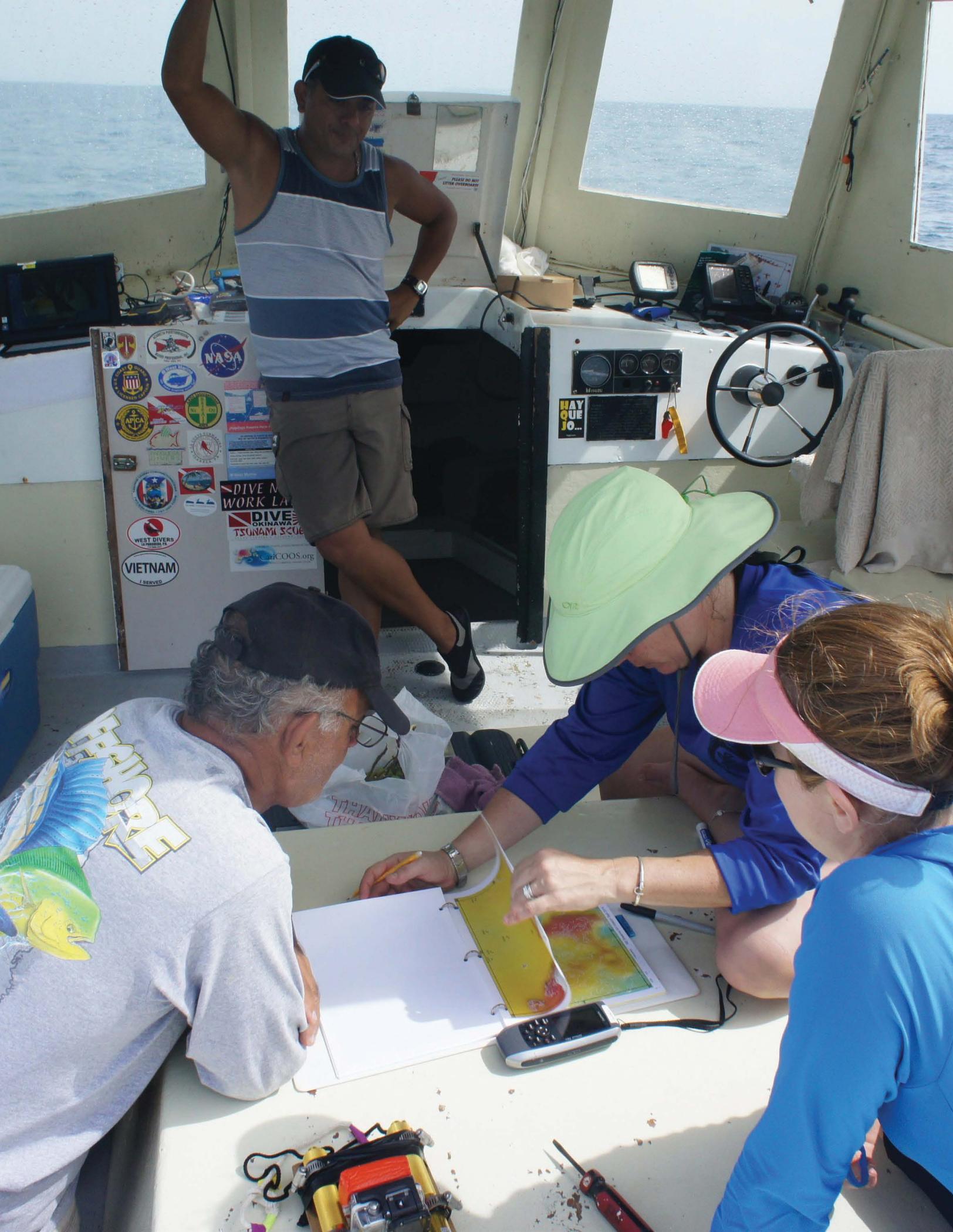


Figure 3.24. The manually digitized a) *shore complex* map and the semi-automated derived b) *open water* map were merged into c) one map for the accuracy assessment and final manual edits. The two maps can be re-separated if needed by a *map zone* attribute in the final product.

3.5. GEOGRAPHIC ZONE MAP

A map of geographic zones in the mapping area was created after the habitat map had been completed. The zone map was manually digitized at 1:4000, using visual interpretation based on the remote sensing imagery, the GV data and the habitat map. The Geographic Zone Map was digitized at a coarser scale level than the habitat map (1:4,000 vs 1:1,000) due to the more generalized zones. The process used to create the zone map is similar to the *Shore Complex* Map process (section 3.1), using similar methods as the habitat map developed in the project area in 2001 (Kendall, et al., 2001). The Geographic Zone mapping effort took advantage of the already complete *Shore Complex* Map by ingesting and modifying the *shore complex* polygons as part of the Zone Map. Once the zone map was completely digitized, the topologies of the polygons were analyzed and cleaned using the ArcGIS Spatial Analyst Toolbox. The "Find Overlapping Features" ArcGIS tool created by the Biogeography Branch was used to remove the overlapping zone boundaries and locate any gaps between polygons. A total of 12 different zone types (see Chapter 2) were identified in the project area.





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CHAPTER 4: ASSESSMENT OF CLASSIFICATION ACCURACY

An independent assessment was conducted to evaluate the thematic accuracy of the benthic habitat map. Thematic accuracy was characterized for major and detailed geomorphological structure, major and detailed biological cover, percent hard bottom, percent coral cover, and dominant coral type.

4.1. FIELD DATA COLLECTION

Given the geographic extent of this project, an Accuracy Assessment (AA) of the draft habitat map was conducted on a representative subset of the total area. This approach has been implemented previously with success (Battista, et al., 2007 and NOAA, 2005). A series of factors were selected by a team of mappers and biologists to assess thematic accuracy (i.e., habitat type, diversity of habitats, range of habitat, oceanographic conditions, and management zones). The draft map included 711 km² of classified habitat, while the subset areas encompassed approximately 442 km², thereby sub-sampling 59% of the total mapped area. All habitat types were represented within the 5 subset areas across the complete mapped area (Figure 4.1). AA boundaries were manually digitized to follow natural coastal contours and included *Mangrove* fringe habitat, where applicable. The overall AA results were extrapolated to the entire mapped area.

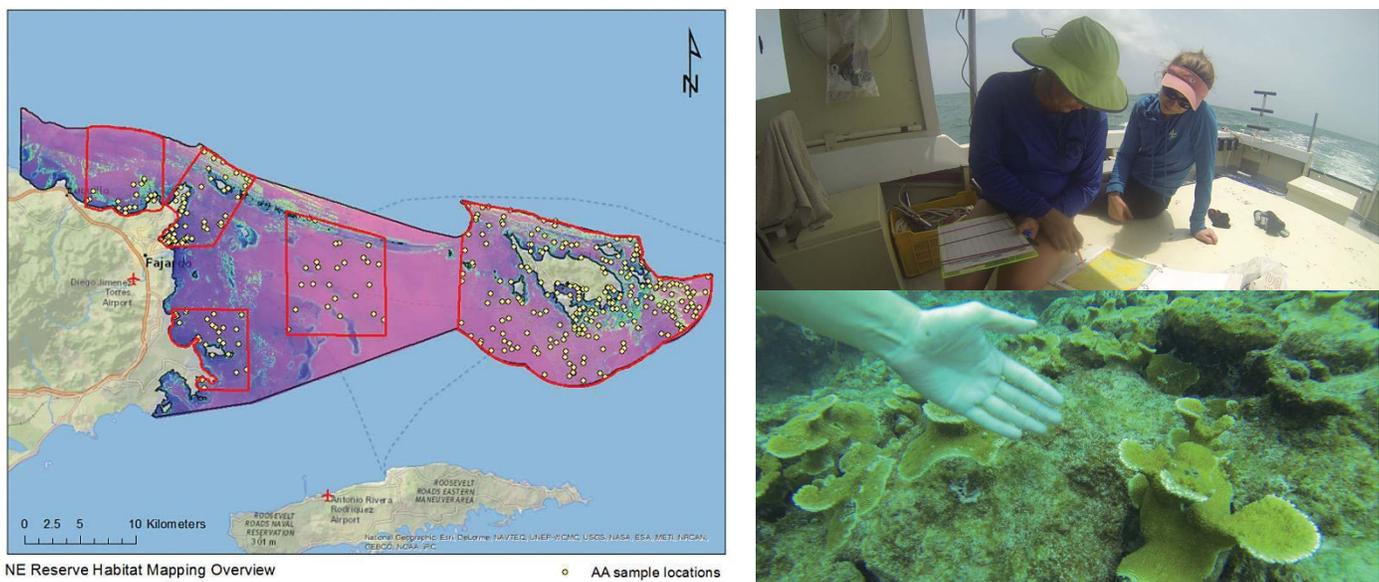


Figure 4.1. a) In September 2014, underwater video was collected at 400 sites within the North East Reserve. These data were used to assess the thematic accuracy of the benthic habitat map of this region; b) scientists developing the sampling plan in the field; and c) *Acropora palmata* colonies recorded on shallow snorkel dives during the shallow AA surveys.

Locations for the AA were determined using an iterative, GIS-based, stratified random sampling technique to ensure that all bottom classifications were evaluated. Twenty-five points were randomly placed within each of the draft map's 14 detailed geomorphological structure classes using XTools Pro v 9.0. No minimum distance was enforced from polygon edges. Classes occupying larger areas were allocated more than 25 points based on the proportional area. A total of 412 sites were sufficiently surveyed to be included in the AA (Figure 4.2). AA data were collected during a field mission that took place from September 2 to September 18, 2014. Similar field sampling protocols were used in collecting the AA data to those used during GV data collection (see section 3.3.6 (pg. 51)). GPS data were logged continuously during video acquisition aboard the survey boat using a Trimble Geo XH. High definition video was also recorded at many sites using a GoPro Hero 1 camera mounted on the drop camera housing. Sites that could not be navigated to by boat were accessed by snorkeling or on foot. Videos at these locations were captured using the GoPro Hero 1 camera and a Canon Power Shot SD1100 enclosed in a waterproof housing.

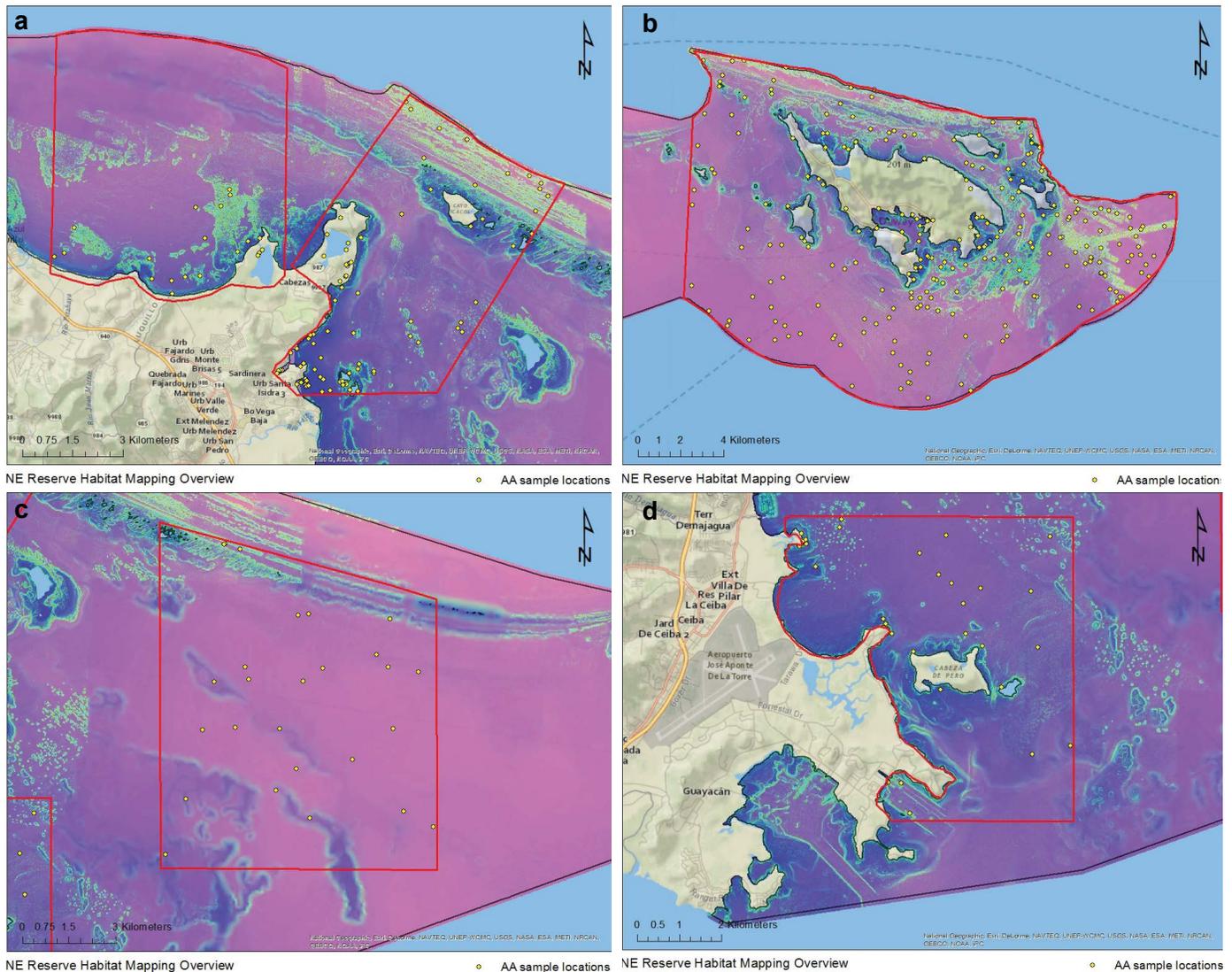


Figure 4.2. Maps show each AA boundary overlaid on the PCA imagery (red polygons): a) northeast Puerto Rico, b) Culebra Island, c) central east coast Puerto Rico, and d) southeast Puerto Rico.

4.2. EVALUATION OF ASSESSMENT DATA

All analyses for this assessment was conducted by an independent scientist, not by the cartographer. The GPS data were processed using Trimble Pathfinder software. GPS data logged during this mission on the Trimble Geo XH receiver were differentially post-processed to the Puerto Rico Continually Operating Reference System station (i.e., station PRFJ) on Fajardo, PR. Individual epochs were logged on the Trimble as the boat drifted over a survey site. These epics were averaged to generate an “average” GPS point. The GPS data were then exported and plotted in ArcGIS along with the corresponding field notes. In some cases, the average point was a suitable representation of the survey site location. However, there were a large number of cases where the AA survey crossed one or more polygon edges. This was due in part to the very high density of lines that resulted from the small MMU and the computer based, semi-automated edge detection process used to create these maps. In these cases, the average GPS point often did not fall into the polygon that encompassed the randomly selected AA site. If necessary, the average point was manually relocated in ArcGIS to the sampled portion of the transect. This location process was corroborated with the Trimble GPS track coupled with time stamped GoPro photos collected in tandem with the SeaViewer camera. Prior to analysis, each video clip was reviewed in concert with the benthic habitat map overlaid on the remote sensing imagery (aerial photos, satellite and LiDAR imagery). Imagery and map overlays were viewed at the scale of feature delineation (1:1,000). Layback from camera cables on a drifting boat, position of boundary delineations by the mapper, and GPS error particularly during snorkels, were all considered in the context of the MMU (100 m²) for the most accurate placement of AA sample sites.

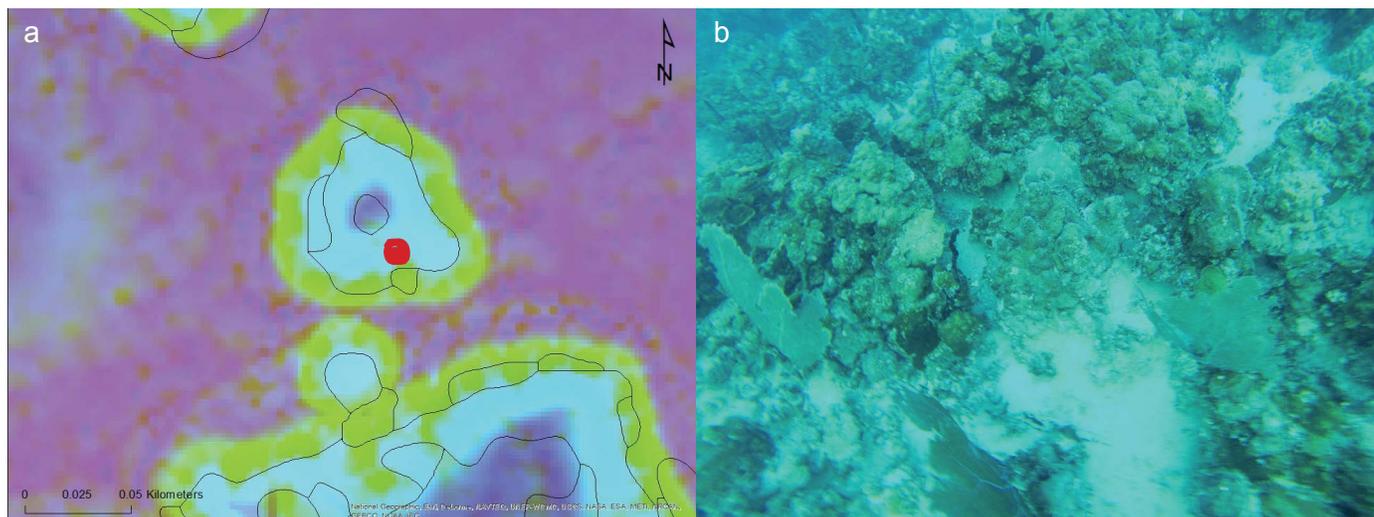


Figure 4.3. a) Map showing an individual patch reef (green perimeter) with the PCA imagery in the background. b) An underwater photo taken at the red point (left) on the individual patch reef.

Biological cover type was identified using the underwater videos from both the SeaViewer and the GoPro, and the patchiness of biological cover was estimated at the polygon level. It was often necessary to adjust the classifications that were initially recorded in the field to reconcile the differences between the video and polygon spatial scales (Figure 4.3). Similar adjustments were sometimes necessary to correctly characterize detailed structure. For example, heterogeneous hardbottom classes, such as *Pavement with Sand Channels*, could not always be correctly classified from the video alone if the vessel/video did not drift over a sand channel. In other cases, additional information on the position, size, and shape of hardbottom features was needed to determine whether the structure should be classified as *Aggregate Reef* or a *Patch Reef* (either individual or part of an aggregated patch reef feature, if below the MMU). Following these adjustments, data were then spatially joined to the benthic habitat layer to extract the map classification at each AA point. Sites that differed between field notes and map classification were evaluated to determine possible sources of disagreement. Some of these disagreements were discussed with the cartographer to make sure that all aspects of the classification scheme were being consistently applied. Classification errors due to line position (i.e., the misplacement of drawn polygon edge) were not categorized separately from thematic errors (i.e., the correct boundary was drawn but the wrong attributes were assigned).

4.3. ANALYSIS OF THEMATIC ACCURACY

The thematic accuracy of the NER benthic habitat map was summarized using error matrices. These error matrices were computed in R stat using the `maptools`, `sp`, `gdata`, `plyr`, `xlsx` and `xlsxjars` packages at each thematic level in the classification scheme (i.e., major and detailed geomorphological structure, major and detailed biological cover, percent hardbottom, percent coral cover and dominant coral type). Overall accuracy, producer's accuracy, and user's accuracy were computed directly from these error matrices (Story and Congalton, 1986). The error matrices were constructed as a square array of numbers arranged in rows and columns. The overall accuracy (P_o) was calculated as the sum of the major diagonal (i.e. correct classifications, divided by the total number of accuracy assessment samples).

The producer's and user's accuracies were calculated to characterize the classification accuracy of individual map categories. The producer's accuracy (omission/exclusion error) is a measure of how well the cartographer classified a particular habitat (e.g., the percentage of times that substrate ground-truthed as *Sand* was correctly mapped as *Sand*). The user's accuracy (commission/inclusion error) is a measure of how often map polygons of a certain habitat type were classified correctly (e.g., the percentage of times that a polygon classified as *Sand* was actually ground-truthed as *Sand*). Each diagonal element was divided by the column total ($n_{j\cdot}$) to yield a producer's accuracy and by the row total ($n_{\cdot j}$) to yield a user's accuracy.

In addition, the Tau coefficient (T_e) was calculated, which is a measure of the improvement of classification accuracy over a random assignment of map units to map categories (Ma and Redmond, 1995). As the num-

ber of categories increases, the probability of random agreement (P_o) diminishes, and T_e approaches P_o . Values of T_e were calculated as follows:

Tau coefficient = $T_e = (P_o - P_r) / (1 - P_r)$,
where $P_r = 1/\text{number of habitat classes}$

The variance of Tau (Ma and Redmond, 1995) was calculated as:

Variance of $T_e = \sigma_r^2 = P_o (1 - P_o) / n (1 - P_r)^2$

Confidence intervals were then calculated for each Tau coefficient at the 95% confidence level ($1-\alpha$), using the following generalized form:

$$95\% \text{ CI} = T_e \pm Z_{\alpha/2}(\sigma_r^2)^{0.5}$$

While stratification ensures adequate evaluation of all map categories, it has the undesired effect of introducing bias into the error matrix based on the different sizes of the areas mapped in each classification (Hay 1979; Card, 1982). A minimum number of sites were targeted within each mapping category, which caused rare map categories to be sampled at a greater density than common map categories. For example, although *Individual Patch Reefs* comprised only 0.4% of the map area (2.5 km²), 6% of the target points were allocated to this habitat. The bias introduced by differential sampling density was removed using the method of Card (1982), which utilizes the proportions of total area covered by each classification. The map marginal proportions were calculated as the area of each map category divided by the total mapped area. The map marginal proportions were also used to calculate confidence intervals for the overall, producer's, and user's accuracies (Card, 1982; Congalton and Green, 1999). This method was used in NOAA's recent accuracy assessments of the Benthic Habitats of Fish Bay, Coral Bay and STEER (Costa, et al., 2013); Buck Island Reef National Monument (Costa, et al., 2012) and Shallow-water Benthic Habitats of Southwest Puerto Rico (Bauer et al., 2012).

The map marginal proportions (π_j) were computed from the GIS layer of the draft benthic habitat map for the following error matrices (major and detailed geomorphological structure, major and detailed biological cover and percent hard bottom) by dividing the area of each category by the total map area. The map areas were exclusive to categories present in the error matrix. Proportional areas were based on the draft assessment and area values may differ slightly in the final map after errors are corrected. The individual cell probabilities (i.e. the product of the original error matrix cell values and π_j , divided by the row marginal or total map classifications per category), were computed for the off-diagonal elements using the following equation:

$$\text{Individual cell probabilities} = \hat{P}_{ij} = \pi_j n_{ij} / n_{-j}$$

The relative proportions of the cell values (within a row of the error matrix) were unaffected by this operation, but the row marginals were forced to the map marginal proportions (i.e. the row total of a particular habitat now equaled the fraction of map area occupied by that habitat, instead of the total number of accuracy assessment points). The estimated true marginal proportions (p_i) were computed as the sum of individual cell probabilities within each column of the error matrix. The π -adjusted overall, producer's, and user's accuracies were then computed from the new error matrix, now populated by individual cell probabilities. The values of the π -adjusted overall and producer's accuracies differ from those of the original error matrix because they have been corrected for the areal bias introduced by the stratified random sampling protocol. The user's accuracy, in contrast, is not affected. The variances and confidence intervals of the overall, producer's, and user's accuracies were then computed from the following set of equations (Card, 1982; Walker and Foster, 2009):

$$\text{Overall Variance} = V(\hat{P}_c) = \sum_{i=1}^r p_{ii} (\pi_i - p_{ii}) / n_i$$

$$\text{Overall Confidence Interval} = \text{CI} = \hat{P}_c \pm 2[V(\hat{P}_c)]^{1/2}$$

$$\text{Producer's Variance} = V(\hat{\theta}_{ii}) = p_{ii} p_i^{-4} [p_{ii} \sum_{j \neq i}^r p_{ij} (\pi_j - p_{ij}) / n_{-j} + (\pi_i - p_{ii})(p_i - p_{ii})^2 / n_{i-j}]$$

$$\text{Producer's Confidence Interval} = \text{CI} = \hat{\theta}_{ii} \pm 2[V(\hat{\theta}_{ii})]^{1/2}$$

$$\text{User's Variance} = V(\hat{\lambda}_{ii}) = p_{ii} (\pi_i - p_{ii}) / \pi_i^2 n_i$$

$$\text{User's Confidence Interval} = \text{CI} = \hat{\lambda}_{ii} \pm 2[V(\hat{\lambda}_{ii})]^{1/2}$$

4.4. ACCURACY RESULTS AND DISCUSSION

4.4.1. Major Geomorphologic Structure

Error matrices for major geomorphological structure are displayed in Tables 4.1 and 4.2. The overall accuracy (P_o) at the major geomorphological structure level was 90.8%. The Tau coefficient for equal probability of group membership was 0.86 ± 0.04 ($\alpha=0.05$). The adjusted overall accuracy, corrected for bias using the final map marginal proportions, was 89.7% ($\pm 3.49\%$) ($\alpha=0.05$). The user's and producer's accuracies were >93% for all categories, except Coral Reef and Hardbottom, where overall accuracy was slightly lower at 70.4%.

4.4.2. Detailed Geomorphologic Structure

Error matrices for detailed geomorphological structure are displayed in Tables 4.3 and 4.4. The overall accuracy (P_o) at the detailed geomorphological structure level was 63.4%, with a Tau coefficient (T_e) of 0.61 ± 0.05 ($\alpha=0.05$). The adjusted overall bias using the true map marginal proportions did not alter the accuracy at 63.7% ($\pm 7.98\%$) ($\alpha=0.05$). Adjusted user's accuracy ranged from a low of 20% to a high of 100%, with *Pavement with Sand Channels*, *Sand with Scattered Coral and Rock*, and *Reef Rubble* having the lowest accuracies among the categories (Table 4.4). *Pavement with Sand Channels* was mostly confused with *Pavement*, *Sand with Scattered Coral and Rock* was mostly confused with *Sand*, which is to be expected given that these are similar categories; but more notably *Aggregated Patch Reefs* were confused with *Pavement* ($n = 9$, Table 4.3).

4.4.3. Major Biological Cover

Error matrices for major biological cover are displayed in Tables 4.5 and 4.6. The overall accuracy (P_o) at the major biological cover level was 87.6%, with a Tau coefficient (T_e) of 0.84 ± 0.04 ($\alpha=0.05$). The adjusted overall accuracy, corrected for bias using the final map marginal proportions, was only slightly lower at 82.7%

Table 4.1. Error matrix for major geomorphological structure.

		Accuracy Assessment (i)				User's Accuracy (%)
		Coral Reef and Hardbottom	Other Delineations	Unconsolidated Sediments	n_{-j}	
map (j)	Coral Reef and Hardbottom	188	0	13	201	93.5%
	Other Delineations	0	30	1	31	96.8%
	Unconsolidated Sediments	23	1	156	180	86.7%
	n_i	211	31	170	n = 412 $P_o = 90.8\%$ $T_e = 0.86 \pm 0.04$	
Producer's Accuracy (%)		89.1%	96.8%	91.8%		

Table 4.2. Error matrix for major geomorphological structure, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category's proportions.

		Accuracy Assessment (i)				User's Accuracy (%)	User's CI ($\pm\%$)
		Coral Reef and Hardbottom	Other Delineations	Unconsolidated Sediments	π_j		
map (j)	Coral Reef and Hardbottom	0.192	0.000	0.013	0.205	93.5%	1.1%
	Other Delineations	0.000	0.158	0.005	0.163	96.8%	1.6%
	Unconsolidated Sediments	0.081	0.004	0.548	0.632	86.7%	3.6%
	p_i	0.272	0.162	0.566	$\pi = 1$ $P_o = 89.7\%$ $CI(\pm) = 3.49\%$		
Producer's Accuracy (%)		70.4%	97.8%	96.7%			
Producer's CI ($\pm\%$)		8.4	7.6	5.9			

Table 4.3. Error matrix for detailed geomorphological structure.

Accuracy Assessment (i)

	Aggregate reef	Aggregated patch reefs	Artificial reef	Individual patch reef	Mud	Pavement	Pavement with sand channels	Reef rubble	Rhodoliths	Rhodoliths with scattered coral and rock	Rock/Boulder	Sand	Sand with scattered coral and rock	Spur and Groove	n_j	User's Accuracy (%)
Aggregate reef	21	1				5	1		1		1	1			31	68%
Aggregated patch reefs	10	11				9	1					1			32	34%
Artificial			18												18	100%
Individual patch reef	6	1		13		2									22	59%
Mud			1		46							2			49	94%
Pavement	4	2		2		23			1		2	2		1	38	61%
Pavement with sand channels	5					9	7							3	24	29%
Reef rubble	1	1						2				6			10	20%
Rhodoliths						4			20			5			31	65%
Rhodoliths with scattered coral and rock						4			4	13		2	1		24	54%
Rock/Boulder	2					1					17				20	85%
Sand		1			3	5		2	2	1	1	36	3		54	67%
Sand with scattered coral and rock		1				4			2			9	5	1	22	23%
Spur and Groove						2	1							21	24	88%
n_i	49	18	19	15	49	68	10	4	30	17	21	64	9	26	$n = 399$	
Producer's Accuracy (%)	43%	61%	95%	87%	94%	34%	70%	50%	67%	76%	81%	56%	56%	81%	$P_o = 63.4\%$	
																$t_e = 0.61 \pm 0.05$

(i) map

Table 4.4. Error matrix for detailed geomorphological structure, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category's proportions.

Accuracy Assessment (i)

	Aggregate reef	Aggregated patch reefs	Artificial	Individual patch reef	Mud	Pavement	Pavement with sand channels	Reef rubble	Rhodoliths	Rhodoliths with scattered coral and rock	Rock/Boulder	Sand	Sand with scattered coral and rock	Spur and groove	π_j	User's Accuracy (%)	User's CI ($\pm\%$)
Aggregate reef	0.0175	0.0001				0.0042	0.0001		0.0001		0.0001	0.0001			0.0259	67.7%	1.08%
Aggregated patch reefs	0.0112	0.0132				0.011	0.0012					0.0012			0.0383	34.4%	1.45%
Artificial			0.0002												0.0002	100.0%	0%
Individual patch reef	0.001	0.0002		0.0021		0.0003						0.0017			0.0423	59.1%	0.30%
Mud			0.0001		0.0397							0.0064			0.0397	93.9%	0.64%
Pavement	0.0147	0.0073		0.0073		0.0844			0.0037	0.0037	0.0073	0.0073		0.0037	0.1394	60.5%	3.62%
Pavement with sand channels	0.0018					0.0032	0.0025							0.0011	0.0085	29.2%	0.52%
Reef rubble	0.0004	0.0004						0.0008				0.0024			0.0039	20%	0.40%
Rhodoliths						0.0203			0.1014	0.0101		0.0254			0.1572	64.5%	4.29%
Rhodoliths with scattered coral and rock						0.0081			0.0081	0.0263		0.0040	0.0020		0.0486	54.2%	2.10%
Rock/Boulder	0.0004					0.0002					0.0032			0.0037	85%	0.24%	
Sand		0.0090			0.0267	0.0446		0.0178	0.0178	0.0089	0.0089	0.3209	0.0267		0.4814	66.7%	7.41%
Sand with scattered coral and rock		0.0012				0.0046			0.0023			0.0104	0.0058	0.0012	0.0554	22.7%	1.14%
Spur and groove						0.0018	0.0009							0.0190	0.0218	87.5%	0.76%
P_i	0.0477	0.0319	0.0010	0.0094	0.0664	0.1824	0.0054	0.0186	0.1341	0.0490	0.0202	0.3742	0.0345	0.0249	$\pi_i = 1$		
Producer's Accuracy (%)	38.8%	41.2%	16.2%	21.9%	59.7%	46.3%	45.7%	4.2%	75.6%	53.6%	15.6%	85.8%	16.7%	76.4%	$P_o = 63.7\%$		
Producer's CI ($\pm\%$)	13.6%	30.2%	26.9%	24.4%	27.2%	14.1%	35.2%	7.6%	22.1%	29.5%	15.9%	15.4%	18.4%	25.3%	$C(\pm) 7.98\%$		

(i) daw

(± 4.4%) ($\alpha=0.05$). Adjusted user's accuracy was >93% for *Algae* and *Mangroves*, but only 50% for *No Cover*. *Algae* and *No Cover* were occasionally confused ($n=20$), as algal mats are often ephemeral and the two classes are characteristically patchy and intermixed. Accuracy of mapped live coral cover class will be discussed in the *Percent Hardbottom and Live Coral Cover* section.

4.4.4. Detailed Biological Cover

Error matrices for detailed biological cover are displayed in Tables 4.7 and 4.8. The overall accuracy (P_o) at the detailed biological cover level was 53.0%, with a Tau coefficient (T_e) of 0.48 ± 0.06 ($\alpha=0.05$). The adjusted overall accuracy, corrected for bias using the final map marginal proportions, decreased slightly to 48.3% ($\pm 7.1\%$) ($\alpha=0.05$) because those classes with the greatest aerial coverage were also the most frequently misinterpreted. Specifically, *Algae* 90-100% misclassified as *Algae* 50-<90% ($n=71$), and vice versa ($n=21$).

Table 4.5. Error matrix for major biological cover.

		Accuracy Assessment (i)					n_j	User's Accuracy (%)
		Algae	Mangrove	Live Coral	No Cover	Seagrass		
map (j)	Algae	248		8	2	7	265	93.6%
	Mangrove		34				34	100.0%
	Live Coral			1			1	100.0%
	No Cover	20			23	3	46	50%
	Seagrass	4			3	26	33	78.8%
	n_i	272	34	9	28	36		
Producer's Accuracy(%)		91.2%	100.0%	11.1%	82.1%	72.2%		
							$n = 379$	
							$P_o = 87.6\%$	
							$T_e = 0.84 \pm 0.04$	

Table 4.6. Error matrix for major biological cover using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category's proportions.

		Accuracy Assessment (i)					π_j	User's Accuracy (%)	User's CI ($\pm\%$)
		Algae	Mangrove	Live Coral	No Cover	Seagrass			
map (j)	Algae	0.5625		0.0181	0.0045	0.0159	0.6011	93.6%	2.1%
	Mangrove		0.0265				0.0265	100.0%	0.0%
	Live Coral			0.0018			0.0018	100.0%	0.0%
	No Cover	0.0840			0.0966	0.0126	0.1932	50.0%	4.3%
	Seagrass	0.0215			0.1612	0.1397	0.1774	78.8%	3.9%
	P_i	0.6680	0.0265	0.0200	0.1173	0.1682			
Producer's Accuracy (%)		84.2%	100.0%	9.13%	82.4%	83.1%			
Producer's CI ($\pm\%$)		4.6%	0.0%	5.8%	24.4%	15.6%			
							$\pi = 1$		
							$P_o = 82.7\%$		
							$CI(\pm) = 4.38\%$		

4.4.5. Percent Hardbottom and Live Coral Cover

Hardbottom habitat comprises approximately 20.5% of the draft map area (Table 4.2). The overall accuracy (P_o) for the percent hardbottom class was 74.9%, with a Tau coefficient (T_e) of 0.70 ± 0.05 ($\alpha=0.05$) (Table 4.9). The adjusted overall accuracy, corrected for bias using the final map marginal proportions, increased to 81.8% ($\pm 4.23\%$) ($\alpha=0.05$) (Table 4.10). This increase relative to the raw matrix (Table 4.9) was due to the large proportion (~63%) of map area classified as 0-<10% hard (i.e. soft bottom) and high accuracy of mapping these bottom types (i.e. *Sand* and *Mud*).

The error matrix for live coral cover is displayed in Table 4.11. The overall accuracy (P_o) for this class was 70.3%, with a Tau coefficient (T_e) of 0.60 ± 0.07 ($\alpha=0.05$). This seemingly high overall accuracy in classification of live coral cover was driven almost entirely by the high accuracy of mapping areas with low or no coral cover (e.g. *Sand*) rather than in mapping areas with high coral cover. There are a dwindling number of areas with significant coral cover in the Caribbean, therefore, *Live coral 50-90%* occurred very rarely in the map ($n=9$, Table 4.11). Locations where live coral is present tend to be very localized and small in area. Caution should be used when considering use of this important, but rare map category because of the negligible sample size in both the map and AA data.

Table 4.7. Error matrix for detailed biological cover.

		Accuracy Assessment (i)											
		Algae 10-50%	Algae 50-90%	Algae 90-100%	Mangrove 10-50%	Mangrove 90-100%	Live Coral 50-90%	No Cover 90-100%	Seagrass 10-50%	Seagrass 50-90%	Seagrass 90-100%	n _j	User's Accuracy (%)
map (j)	Algae 10-50%	10	8	8					1			27	37.0%
	Algae 50-90%	7	51	71			6	1		2		138	37.0%
	Algae 90-100%	4	21	68			2	1	1	2	1	100	68%
	Mangrove 10-50%				0							0	0%
	Mangrove 90-100%				2	32						34	94.1%
	Live Coral 50-90%						1					1	100%
	No Cover 90-100%	10	4	6				23	2	1		46	50%
	Seagrass 10-50%			1					1	1		3	33.3%
	Seagrass 50-90%		1	1						0	5	7	0%
	Seagrass 90-100%		1					2		5	15	23	65.2%
	n _i	31	86	155	2	32	9	28	5	10	21	n = 379	
	Producer's Accuracy (%)	32.3%	59.3%	43.9%	0%	100%	11.1%	82.1%	20%	0%	71.4%	P _o = 53.0% t _e = 0.48 ± 0.06	

Table 4.8. Error matrix for detailed biological cover, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category's proportions.

		Accuracy Assessment (i)														
		Algae 10-50%	Algae 50-90%	Algae 90-100%	Mangrove 10-50%	Mangrove 50-90%	Mangrove 90-100%	Live Coral 50-90%	Live Coral 90-100%	No Cover 90-100%	Seagrass 10-50%	Seagrass 50-90%	Seagrass 90-100%	π _j	User's Accuracy (%)	User's CI (±%)
map (j)	Algae 10-50%	0.076	0.061	0.061							0.008			0.205	37.0%	5.6%
	Algae 50-90%	0.012	0.085	0.119				0.010		0.002		0.003		0.231	37.0%	2.7%
	Algae 90-100%	0.007	0.035	0.113				0.003		0.002	0.002	0.003	0.002	0.166	68.0%	2.4%
	Mangrove 10-50%				0									0	0%	0%
	Mangrove 50-90%					0								0	0%	0%
	Mangrove 90-100%				0.001		0.022							0.024	94.1%	5.9%
	Live Coral 50-90%							0.002						0.002	100%	0%
	Live Coral 90-100%								0					0	0%	0%
	No Cover 90-100%	0.042	0.017	0.025						0.097	0.008	0.004		0.194	50%	4.3%
	Seagrass 10-50%			0.006							0.006	0.006		0.018	33.3%	2.7%
	Seagrass 50-90%		0.005	0.005								0	0.024	0.034	0%	0%
	Seagrass 90-100%		0.005							0.011		0.027	0.082	0.126	65.2%	4.2%
	n _i	0.136	0.208	0.329	0.001	0	0.022	0.015	0	0.117	0.024	0.038	0.108	π = 1		
	Producer's Accuracy (%)	55.7%	70.1%	91.2%	0%	0%	100.0%	11.6%	0%	83.0%	25.2%	59.5%	76.2%	P _o = 48.3%		
CLPA	22.5%	10.9%	6.0%	0%	0%	8.6%	7.0%	0%	24.3%	38.4%	29.1%	20.4%	CI(±) = 7.05%			

4.4.6. Live Coral Cover Type

Hard or soft coral dominance was classified when live coral cover was estimated to be >10%. This class was included in a previous mapping effort because it was requested by the National Park Service in St. John, USVI and was included in this mapping effort as continued experimentation in it is interpretation and value. The error matrix for this class is displayed in Table 4.12. Its overall accuracy (P_o) was 72.2 %, with a Tau coefficient (T_e) of 0.62 ± 0.07 ($\alpha=0.05$, $n=320$). It is important to emphasize that the high overall accuracy was driven mainly by the large number of sites lacking coral cover. This is much easier to classify compared to the dominant coral type when hard and soft are often intermixed (128 out of 320 sites).

Additionally, there were cases where overall accuracy and producer's accuracy were corrected for bias using the category's proportions where hard/soft dominance should have been assessed but wasn't (i.e. User classified coral >10% while Producer classified coral <10% cover), as well as cases where dominance was assessed but should not have been (i.e. Producer classified coral >10% while User classified coral >10% cover). Of greater importance was the discrepancy in distinguishing between hard and soft coral dominated areas. Producer's accuracy for identifying areas of hard coral dominance (the bottom type which garners the most interest) was 78.5% ($n=65$), while User's accuracy for hard corals was 59.3% ($n=86$) (Table 4.12). Since so few points occurred in this category, these numbers may be biased and additional assessment should be conducted for this category specifically to better understand the utility of this classification.

Table 4.9. Error matrix for percent hardbottom.

		Accuracy Assessment (i)						n_j	User's Accuracy (%)
		0-10%	10-30%	30-50%	50-70%	70-90%	90-100%		
map (j)	0-10%	156		2	3	10	8	179	87.2%
	10-30%	1	2			1		4	50%
	30-50%			0					0%
	50-70%			1	7	2	1	11	63.6%
	70-90%	4		1	11	34	24	74	45.9%
	90-100%	8		1	3	14	85	111	76.6%
	n_i	169	2	5	24	61	118	n = 379	
Producer's Accuracy (%)	92.3%	100%	0%	29.2%	55.7%	72.0%	$P_o = 74.9\%$ $t_e = 0.70 \pm 0.05$		

Table 4.10. Error matrix for percent hardbottom, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category's proportions.

		Accuracy Assessment (i)						π_j	User's Accuracy (%)	User's CI ($\pm\%$)
		0-10%	10-30%	30-50%	50-70%	70-90%	90-100%			
map (j)	0-10%	0.658		0.008	0.013	0.042	0.033	0.755	87.2%	4.1%
	10-30%	0.002	0.003			0.002		0.007	50%	1.2%
	30-50%			0				0.002	0%	0%
	50-70%			0.002	0.012	0.003	0.002	0.019	63.6%	1.5%
	70-90%	0.003		0.001	0.011	0.033	0.023	0.071	45.9%	1.6%
	90-100%	0.011		0.001	0.004	0.018	0.112	0.146	76.6%	1.9%
	p_i	0.674	0.003	0.012	0.039	0.098	0.170	$\pi = 1$		
Producer's Accuracy (%)	97.6%	100%	0%	30.8%	33.2%	65.7%	$P_o = 81.8\%$			
Producer's CI ($\pm\%$)	5.6%	100%	0%	16.6%	11.3%	10.8%	$CI(\pm) = 4.23\%$			

4.4.7. Conclusions

The new benthic habitat maps for the NER have accuracy percentages that make them suitable for a wide range of scientific and management applications. These maps are a valuable tool for local managers in providing a baseline inventory of the major marine resources within the Reserve, particularly in light of the recent designation of the reserve as a NOAA Habitat Focus Area.

The map assists as a tool to manage and protect coral reef ecosystems, particularly hardbottom reef zones, as well as seagrass beds and coastal mangroves. *Mangrove* habitat resulted in 100% producer and user accuracies and *Coral Reef and Hardbottom Habitat* at 70% corrected accuracy. *No Cover* was occasionally misclassified as *Algae* 10-50% (Tables 4.5 and 4.6) which impacted the accuracy of this habitat. Additional discrepancies at a higher level of assessment between *Coral Reef and Hardbottom* and *Unconsolidated Sediment* (Table 4.1 and 4.2) lowered the overall accuracy at the major structure level. Within the percent hardbottom categories, the habitat map was less accurate at the ends of the percent classification continuum, (i.e. 10-50%, 50-90%, >90-100% and 90-100%, Tables 4.7 and 4.8) particularly for *Algae*.

While the overall accuracy of the dominant coral type class was high (72.2%), these results are skewed due to the large number of sites with little to no coral cover that are included in the assessment of this category. This suggests it is very challenging to accurately map the true representation of this category, even with current mapping technology, source data, and density of ground validation.

Table 4.11. Error matrix for live coral cover.

		Accuracy Assessment (i)						
		Coral reef and hardbottom 0-10%	Coral reef and hardbottom 10-50%	Coral reef and hardbottom 50-90%	Coral reef and hardbottom 90-100%	Unconsolidated sediment 0-10%	n _j	User's Accuracy (%)
map (j)	Coral reef and hardbottom 0-10%	67	26	5		12	110	60.9%
	Coral reef and hardbottom 10-50%	38	44	3		1	86	51.1%
	Coral reef and hardbottom 50-90%			1			1	100%
	Coral reef and hardbottom 90-100%				0		0	0%
	Unconsolidated sediment 0-10%	9	4	0		120	133	90.2%
n _i		114	74	9	0	133	n = 330	
Producer's Accuracy (%)		58.8%	59.5%	11.1%	0%	90.2%	P _o = 70.3% t _e = 0.60 ± 0.07	

Table 4.12. Error matrix for coral dominance.

		Accuracy Assessment (i)					
		Hard coral	Soft coral	Mixed	No cover	n _j	User's Accuracy (%)
map (j)	Hard coral	51		28	7	86	59.3%
	Soft coral		13	8	3	24	54.2%
	Mixed	10	15	39	3	67	58.2%
	No cover	4	8	3	128	143	89.5%
	n _i	65	36	78	141	n = 320	
Producer's Accuracy (%)		78.5%	36.1%	50%	90.8%	P _o = 72.2% t _e = 0.62 ± 0.07	

Live coral cover (hard and soft corals combined) also resulted in a high overall accuracy of this class but it is a challenging category in that the accuracy is driven primarily by two factors: first, soft bottom sites comprised ~40% of the total number of sites in the assessment, and of course, contain virtually no coral (170 of 412 sites). This has the effect of amplifying the overall accuracy in the confusion matrix, but is based on correctly identifying the absence of coral in habitats such as *Sand* and *Mud*. Secondly, the percent divisions of coral cover (i.e., 0-10%, 10-50%, 50-90%) give a false confidence in the accuracy of this attribute. The vast majority of reefs in the Caribbean have less than 10% coral cover (Jackson et al., 2014), the lowest category, making this an easy choice when mapping. While this class can still be very useful because it accurately predicts coral absence, caution must be used when applying this variable to quantify coral presence, as it may not fully capture this variable. For this reason, the presence of any *Acropora palmata* and *A. cervicornis* colonies seen in the video footage was noted in the map as valuable qualitative data on the specific locations of this critically endangered species.

The MMU restriction was set to 100 m². The core of the scheme was originally designed for use with a 4,047 m² (1 acre MMU) and several of the categories are best depicted at this larger MMU (1,000 m² MMU has also been successfully applied). For example, *Pavement with Sand Channels* and *Spur and Groove* can be separated into their sand and hard bottom components when a 100 m² MMU is applied, so previous mapping efforts at the same spatial scale (100 m² MMU) merged these complement habitat classes based on visual assessment and manual editing (Costa et al., 2013; Bauer et al., 2012). Manual editing by the cartographer was not sufficiently conducted to merge these particular habitats consistently. The manual editing conducted in this instance was based on a computer assisted “best fit neighbor” using the remote sensing algorithms. This method proved inconsistent in areas where the imagery resolution was poor due to excessive water depth, cloud cover or high turbidity. It is recognized that manual editing by the cartographer, rather than a computer assisted method, is a key step in the process for the classification scheme to work effectively with the finer MMU for similar mapping projects in the future but it is debatable whether this small MMU works effectively with this highly detailed classification scheme.

Habitats (*Aggregate Reef* and *Aggregated Patch Reefs*) that look similar in the source imagery were often confused. These high relief habitats share a similar spectral signature and are sometimes difficult to classify due to depth limitations of the imagery or limited visibility where these habitats commonly co-occur. Results here show that the existing mapping approach cannot consistently distinguish between similar bottom types, particularly those where gradual transitions exist. Using fewer, more broadly encompassing categories is more effective and accurate than attempting to use several, more narrowly defined ones in these cases. Another common error was the misclassification of *Pavement* and *Pavement with Sand Channels*, which require accurate positioning and clear imagery to identify the sand channels in the habitat configuration. *Sand* and *Sand with Scattered Coral and Rock* likewise were often confused because they are often patchy, are not uniformly distributed into unique spatial boundaries, and can be interspersed within adjacent categories of varying percent hardbottom and coral cover.

The level of accuracy for detailed structure (63.4%, [63.7% adjusted], Tables 4.3 and 4.4), was lower than that of other recent NOAA benthic habitat maps in Southwest Puerto Rico (83%, [82% adjusted]; Bauer et al., 2012); Vieques, (78.0% [88.8% adjusted] Bauer and Kendall, 2010), St. John, US Virgin Islands (86%, [89% adjusted]; Zitello et al., 2009), and the Florida Keys (86% [92% adjusted]; Walker and Foster, 2009). This can be attributed to the heavy reliance on the computer model and limited manual edits in the post processing phase by the cartographer as a function of the large scale of the project and smaller MMU. The accuracy assessment survey area was limited by time and budget constraints. Ideally, AA sites would be selected from the complete mapped area, but sub-sampling and extrapolating these results to the larger mapped area may account for the lower accuracy results relative to previous studies. For additional details on accuracy assessment methods and computational details, see the literature cited section.





CHAPTER 5: RESULTS AND DISCUSSION

5.1. RESULTS

The new benthic habitat map for Northeast Puerto Rico and Culebra Island characterizes approximately 744 km² of seafloor, including 250 km of digitized shoreline surrounding 210 islands and rock outcrops. The new map covers 545 km² of previously unmapped benthic habitats, and provides an update to an additional 170 km² benthic habitats that were mapped at lower spatial resolution in 2001 (Table 5.1). Six percent of the seafloor in the mapping area was classified as *Unknown* due to insufficient quality of the available remote sensing imagery. The new data also includes 2,869 GV data points extracted from 1,817 underwater video transects and observations collected during three separate field efforts. The GV data includes 461 observations for ESA listed *Acropora* corals, as well as detailed habitat information, fauna and water visibility observations. Twenty-five percent (183 km²) of the habitat map covers the seafloor inside the boundaries of the Northeast Reserves; the remaining 75% (561 km²) of this habitat map describes the seafloor outside the reserve boundaries.



Hermit crab in a seagrass bed with scattered corals.

The overall habitat map accuracies (corrected for proportional bias) as measured by the accuracy assessment were 90% for major geomorphological structure, 64 % for detailed geomorphological structure, 82 % for percent hard-bottom, 71% for topographic complexity, 83% for major biological cover, and 48% for detailed

Table 5.1. Comparison statistics between the Puerto Rico and the U.S. Virgin Islands habitat map from 2001 (Kendall, et al., 2001) and the new habitat map developed in 2015.

	Metric	2001 Map	2015 Habitat Map	2015 Zone Map
Mapping	Imagery Acquisition Date	1999	2011-2013	2011-2013
	Spatial Resolution of Optical Imagery	2.4 m	0.3 - 2 m	0.3 - 2 m
	Spatial Resolution of Bathymetry	-	4-100 m	4-100 m
	Mean Depth of Mapped Area	11.7 m	19.3 m	19.3 m
	Max Depth of Mapped Area	35.5	41.4	41.4
	Scale of Delineation	1:6,000	1:1,000	1:6,000
	MMU	4,046 m ²	100 m ²	4,046 m ²
Habitat Features	Classified Area (within project area)	170 km ²	705 km ²	744 km ²
	Unknown Area (within project area)	586 km ²	49 km ²	0 km ²
	Number of Distinct Classes	23	1004	11
	Number of Polygons	845	86,363	851
	Total Perimeter of Polygons	2,008 km	23,149 km	3,120 km
	Mean Area of Polygons (m ²)	223,170 m ²	8,136 m ²	999,291 m ²
	Median Area of Polygons (m ²)	33,700 m ²	320 m ²	12,603 m ²

biological cover. The percent live coral cover and dominant coral type had 76% and 72% accuracy respectively. The map was adjusted based on information from the accuracy assessment to further improve the accuracy of the final map products.

The accuracy numbers for major structure and major cover are similar to the other benthic habitat maps created by NCCOS Biogeography Branch (Battista, et al., 2007; Bauer and Kendall, 2010; Costa, et al., 2012, 2013; Zitello, et al., 2009), while detailed geomorphological structure and detailed biological cover diverged significantly from previous efforts. The final deliverables for this project are available to the public: (1) on the web (<http://coastalscience.noaa.gov/projects/detail?key=258>) and (2) through an interactive, web-based map

application (<http://maps.coastalscience.noaa.gov/biomapper/biomapper.html?id=prne>). Brief descriptions of these deliverables are listed in Table 5.2.

5.1.1. Habitat Overview

The seafloor in the mapping area consisted of 70% (519 km²) unconsolidated sediments (hereafter referred to as softbottom), 24 % (176 km²) coral reef and hardbottom and 0.1 km² of artificial (man-made) features (Figure 5.1).

The remaining 6% (49 km²) was classified as *Unknown* in the habitat map due to insufficient remote sensing data, however, the GV data indicate that a majority of the *Unknown* areas are low relief reef habitats with low coral cover. A majority (82%, 605 km²) of the project area was located in the Bank/Shelf geographic zone, followed by *Reef Ridge Complex* zone (10%, 70 km²) and fore reef zone (3%, 25 km²) (Figure 5.2). A majority of the reefs with high relief and high coral cover are located outside the Northeast Reserves boundaries, as well as a majority of the areas covered by seagrass. Almost half of the 210 islands and rock outcrops mapped were located within the Northeast Reserves boundaries.

Table 5.2. List of products made available to the public and to managers as a result of this mapping project.

Data Type	Item	Format	Quantity
Map	Benthic Habitat Map 2015	GIS shapefile	1
	Geographic Zone Map 2015	GIS shapefile	1
	Habitat Symbology Layers	GIS layer files	10
Imagery	Satellite Seafloor Mosaic	GeoTiff	1
	Bathymetry Model (Depth)	GeoTiff	1
	Bathymetry Model (Uncertainty)	GeoTiff	1
	Classified GV video data (2,471 points)	GIS shapefile	1
Field Data	Classified AA video data (398 points)	GIS shapefile	1
	Compressed Video of Seafloor (GoPro, SeaViewer)	.mp4	1,827
	Seafloor photos (GoPro 12 MP)	jpegs	30,200
	Positions for seafloor photos	GIS shapefile	1
Online Map	Online Interactive Map Project	Online	1
Reporting	FGDC-compliant Metadata for GIS Files	Text files	7
	Final Report	PDF	1

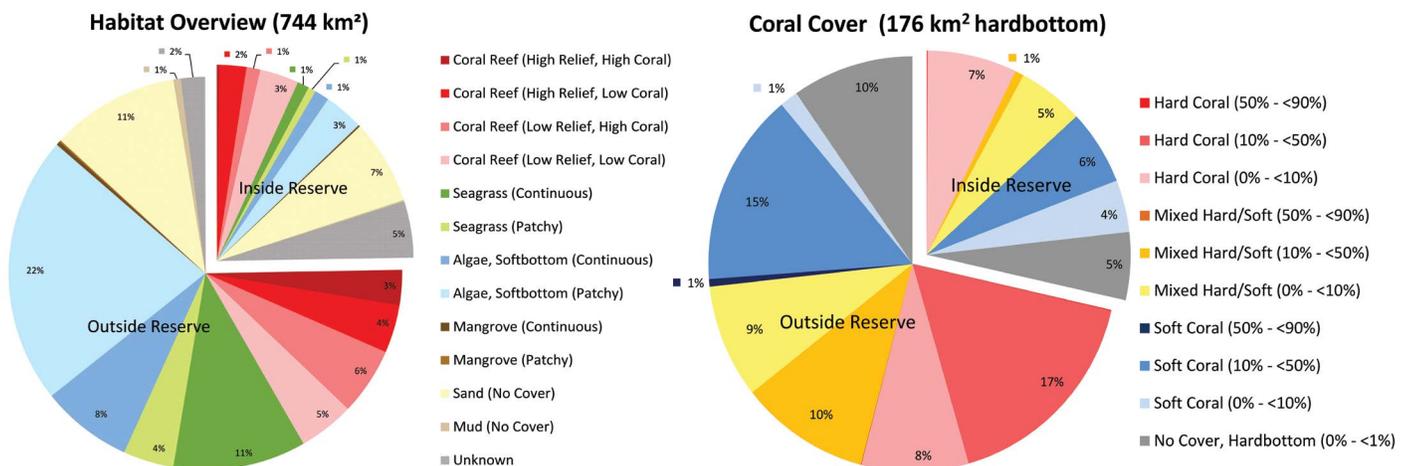


Figure 5.1. The pie charts show the distribution of benthic habitats (left) and live coral cover (right) inside and outside the Northeast Reserves.

Hardbottom Overview

A quarter (24%, 176 km²) of the area was mapped as hard bottom. The hardbottom habitats consisted of 33% (65 km²) low relief reefs with high coral cover (>10%), 28% (63 km²) low relief reefs with low coral cover (<10%), 14% (26 km²) moderate to high relief reefs with low coral cover, and 13% (23 km²) high relief reefs with high coral cover. High to very high *Topographically Complex* reefs comprised only 1.5 % (2.7 km²), and reefs dominated by live corals (>50% cover) comprised less than 0.7% (1.3 km²) of the hardbottom areas. The majority (99.3%) of the hardbottom areas were dominated by algae cover. The most common hardbottom type from a geomorphological perspective was *Pavement* (62%, 109 km²) followed by *Aggregate Reef* (11%, 20 km²), *Aggregated Patch Reefs* (10%, 18 km²) and *Spur And Groove* (9%, 16 km²). *Individual Patch Reefs* made up 1.5% (2.5 km²) of the hardbottom area.

Softbottom Overview

Three quarters (76%, 519 km²) of the known project area was mapped as soft bottom. Half the softbottom habitats mapped consisted of sand or rhodoliths colonized by algae (49%, 252 km²) followed by uncolonized sand (25%, 130 km²), seagrass beds (24%, 124 km²), uncolonized mud (1%, 5.2 km²) and mangroves (0.8%, 4.3 km²). The most common softbottom type from a geomorphological perspective was sand (65%, 338 km²), followed by rhodoliths (22% 114 km²).

See Appendix A.1 and A.2 , and Figure 5.1 for a statistical summary of the mapped habitats, and Figures 5.3, 5.4 and Figure 5.12 for maps of the described hard and softbottom habitats inside and outside the Northeast Reserves.

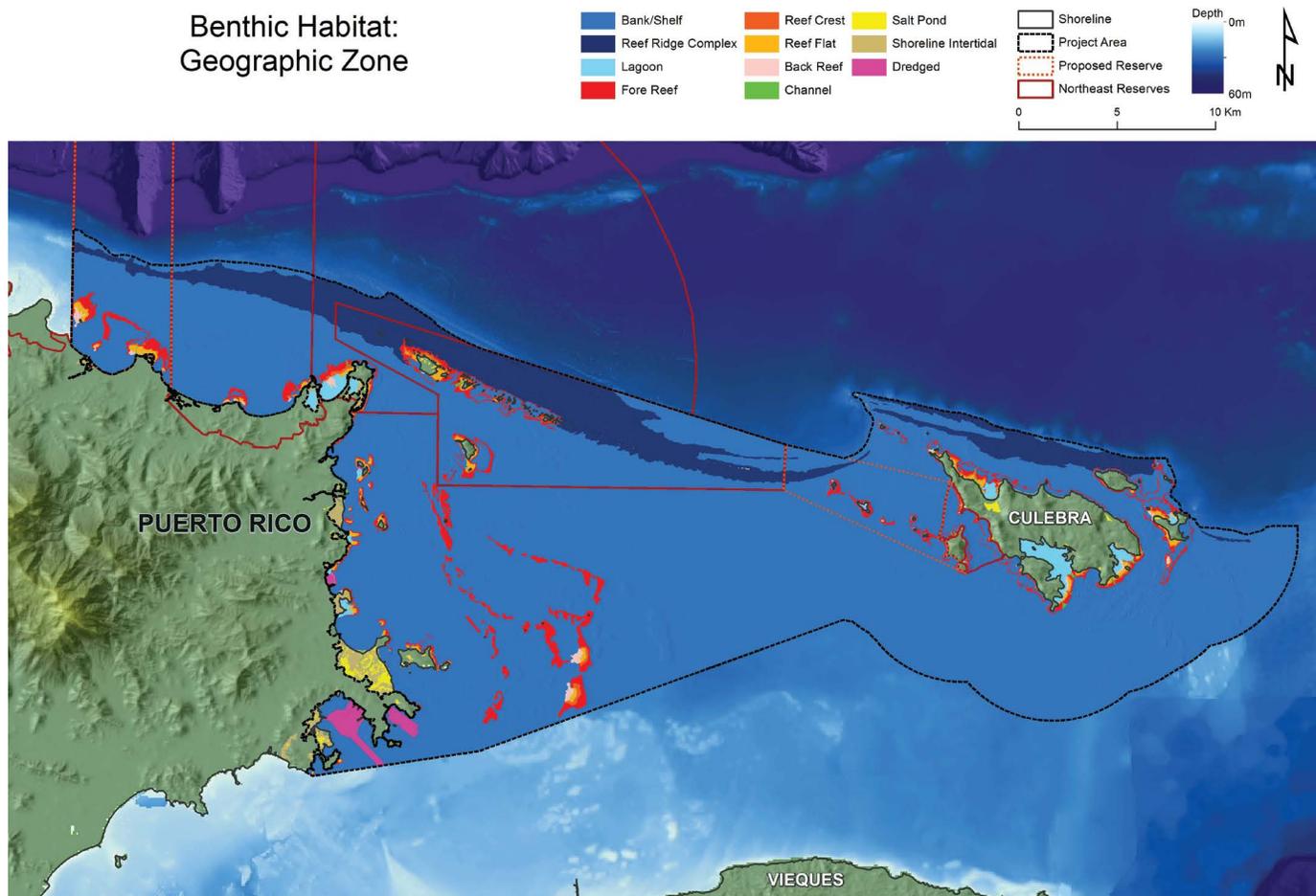


Figure 5.2. Geographic Zones for NEPR and Culebra. The map includes a new addition to the zone classification scheme, *Reef Ridge Complex* (dark blue), which made up 10% of the area, largely consisting of a relict shoreline (Kaye, 1959).

A Closer Look at Corals

While 99.3 % of all hardbottom areas were predominantly colonized by algae, and only 0.7% by live coral, coral cover was still mapped to be greater than 10% for half of the mapped hardbottom area. The mapped distribution of hard versus soft corals (Dominant Coral Type) on the hard bottom areas was 33% *Hard Corals*, 32% *Soft Corals* and 25% *Mixed Hard/Soft Corals*. An additional 10% (2.3% of the total mapped area) had no coral cover (<1% live coral cover). It was also noted that a majority of the GV observations from the 35 km² area mapped as *Unknown* on the north coast of Puerto Rico was classified as low relief reefs (mostly pavement) with no coral cover (<1% live coral cover). The exceptionally low coral cover in this area is likely connected to local impact from land based sources of pollution (Warne, et al., 2005) and the low visibility observed in this region (Figure 5.6). The percent coral cover for *No Cover* (<1% coral) is approximate and can be interpreted as a site with no or very low coral cover, though important ESA corals can still be present (see Chapter 2 for a more detailed definition of coral cover).

Benthic Habitat Overview

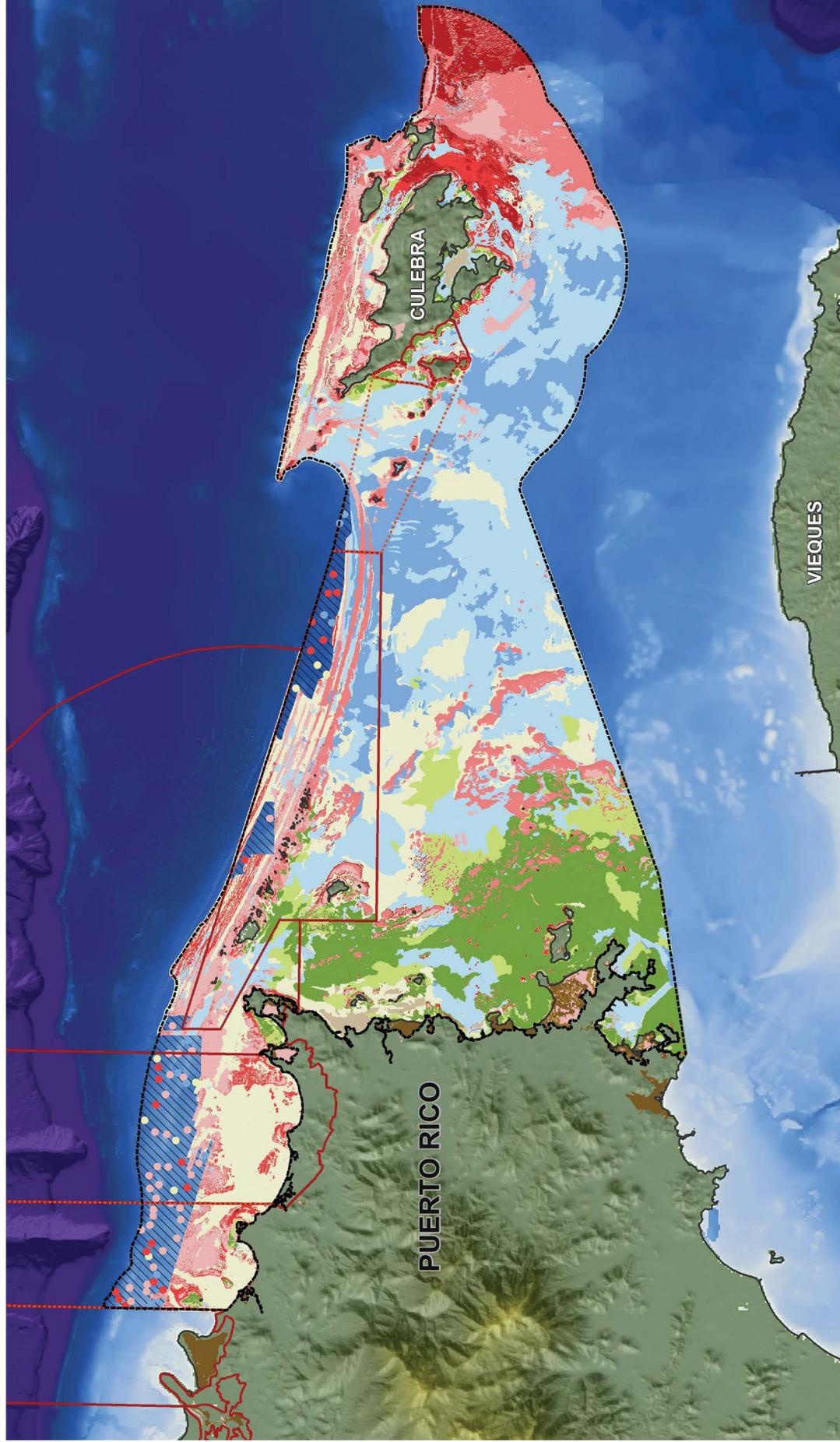
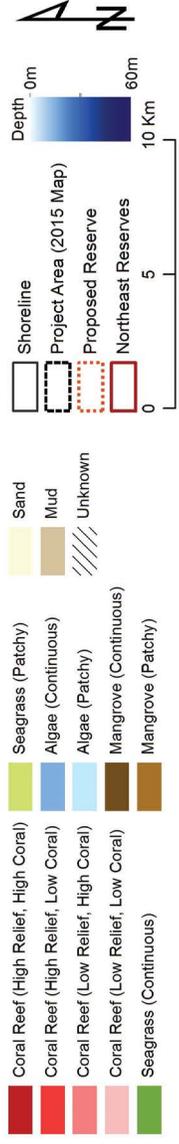


Figure 5.3. The map shows an overview of the benthic habitats of NEPR and Culebra Island derived from a number of different attributes from the classification scheme. A detailed description of the habitat definitions can be found in Chapter 2, Table 2.2 (pg. 31).

**Benthic Habitat:
Percent Coral Cover,
Dominant Coral Cover**

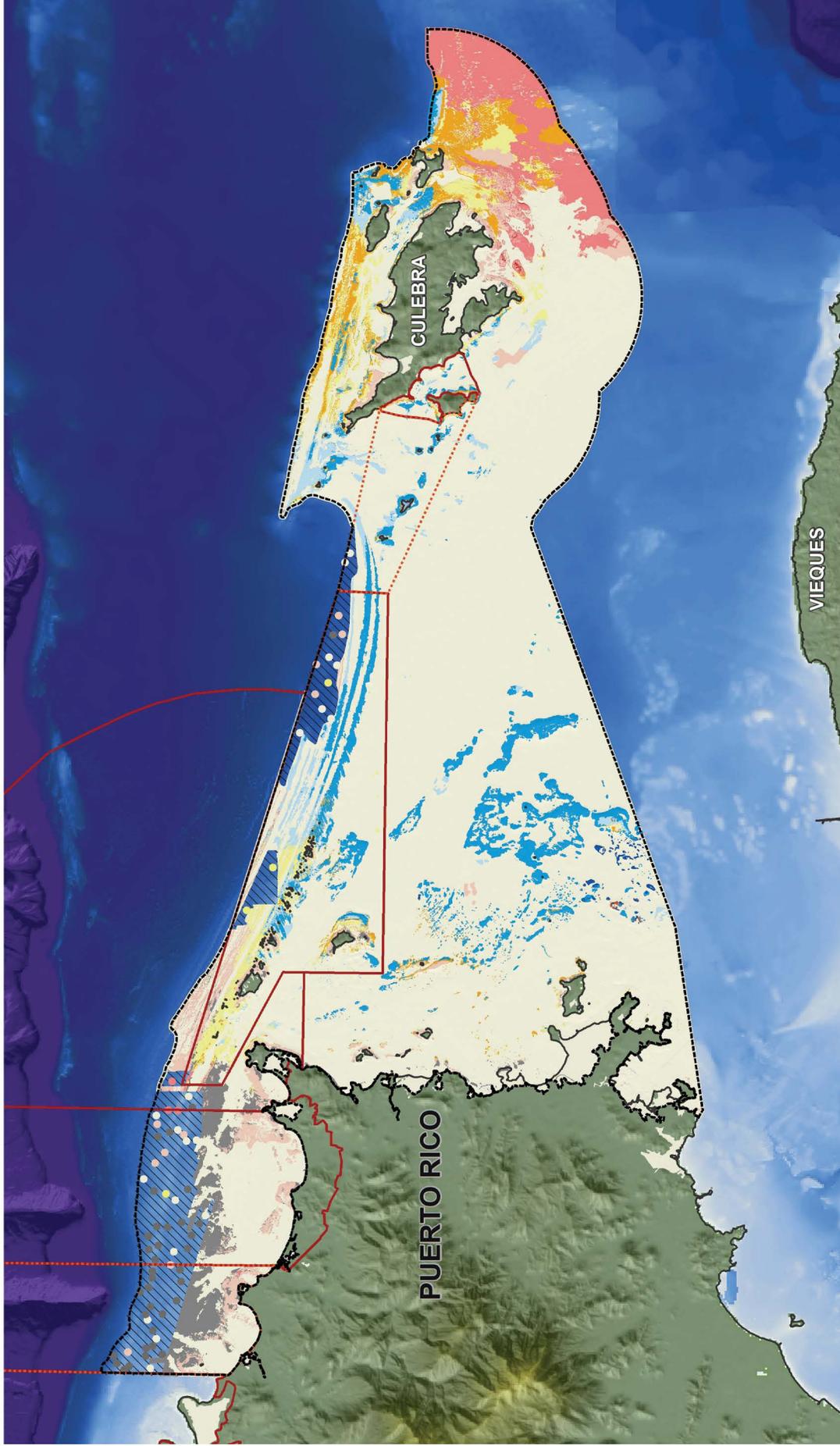
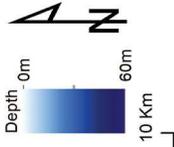
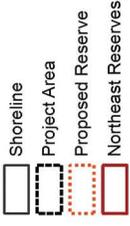
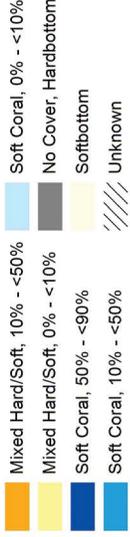


Figure 5.4. The map shows percent live coral cover combined with dominant coral cover (grouped into hard corals, soft corals, mixed hard/soft coral and no cover). The colored points in the *Unknown* area represent coral information from GV data observations.



Juvenile Angel fish and large sponge on the reef.

ESA Corals

There were 263 *Acropora cervicornis* (Staghorn coral) and 198 *Acropora palmata* (Elkhorn coral) sightings in the project area (Figure 5.5). A majority of those observations were made around Culebra Island (187 *A. cervicornis*, and 128 *A. palmata* sightings), though there was a fair amount of sightings around the Cordillera islands, as well as the reef areas in the southeastern part of the NEPR region (49 *A. cervicornis* and 66 *A. palmata* sightings). The maximum depth at which *Acropora* were observed was 23 m for *A. cervicornis* (mean depth 7 m) and 17 m for *A. palmata* (mean depth 2 m).

Other Observations

Fauna observations, co-occurring biological cover as well as water visibility observations were made for all GV data. These data combined with the habitat map can potentially contribute to a deeper ecological understanding of the region, but they are not analyzed in great detail for this report. Figure 5.7 shows all recorded fauna observations; however, sightings of large fish including sharks are generally rare throughout the mapping area. The co-occurring observations of biological cover provided additional data for habitats that did not show up in the major biological class, for example sponges, reefs with zoanths, and algae beds partly covered by seagrass. Co-occurring cover is displayed as point data in Figure 5.8.

Water visibility observations indicate areas of low visibility observed from the underwater videos. The attempt to distinguish moderate visibility from high visibility was inconsistent, so these two classes were merged for the final data set. Nearshore areas around north and northeast Puerto Rico, as well as some of the bays in Culebra were regions in which low visibility and poor water quality were observed. In Figure 5.6 field observations of low coral cover, low visibility and presence of zoanths have been combined to show impacted areas (zoanths can be expected to increase on reefs with elevated nutrient concentrations) (Linton and Warner, 2003). This is an example of how habitat data could potentially be used to locate areas that have been impacted by anthropogenic factors such as land based sources of pollution and sediments. Further research is needed to validate this data.

5.1.2. Habitat By Region

The map statistics have been divided into three geographical regions and by reserve status (i.e. inside or outside the current Northeast Reserves boundaries at the time of this report) in order to present the data in a spatial context. The geographical regions were derived using a 3 nm shoreline buffer to capture the nearshore areas around Culebra and mainland Puerto Rico, as well as the open water area between the two islands. The three regions are hereafter referred to as NEPR, Offshore and Culebra (Figure 5.9). Maps and statistical summaries are available for all habitat classes in Figures 5.12-5.17, tables with these statistics are also found in Appendix A.1. Maps for combined habitat classes (habitat overview, biological cover and coral cover) are found in Figures 5.2, 5.3 and 5.8, a table with statistics from these maps are found in Appendix A.2.

Field Data: Underwater Video Acropora Observations

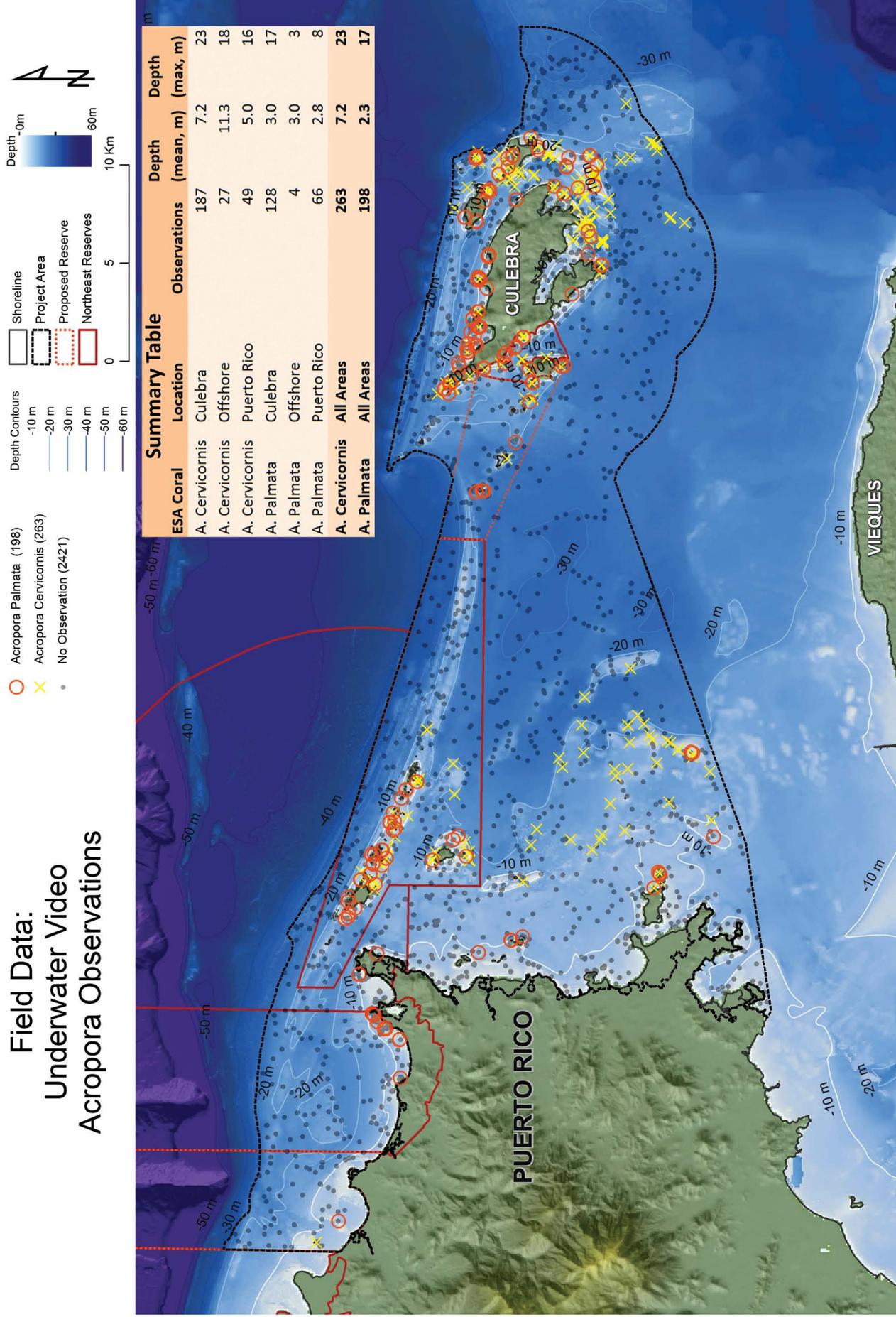


Figure 5.5. *Acropora palmata* and *Acropora cervicornis* sightings derived from a total of 2,869 underwater video observations in the project area (GV and AA data). See Figure 5.9 for an explanation of the geographical regions used.

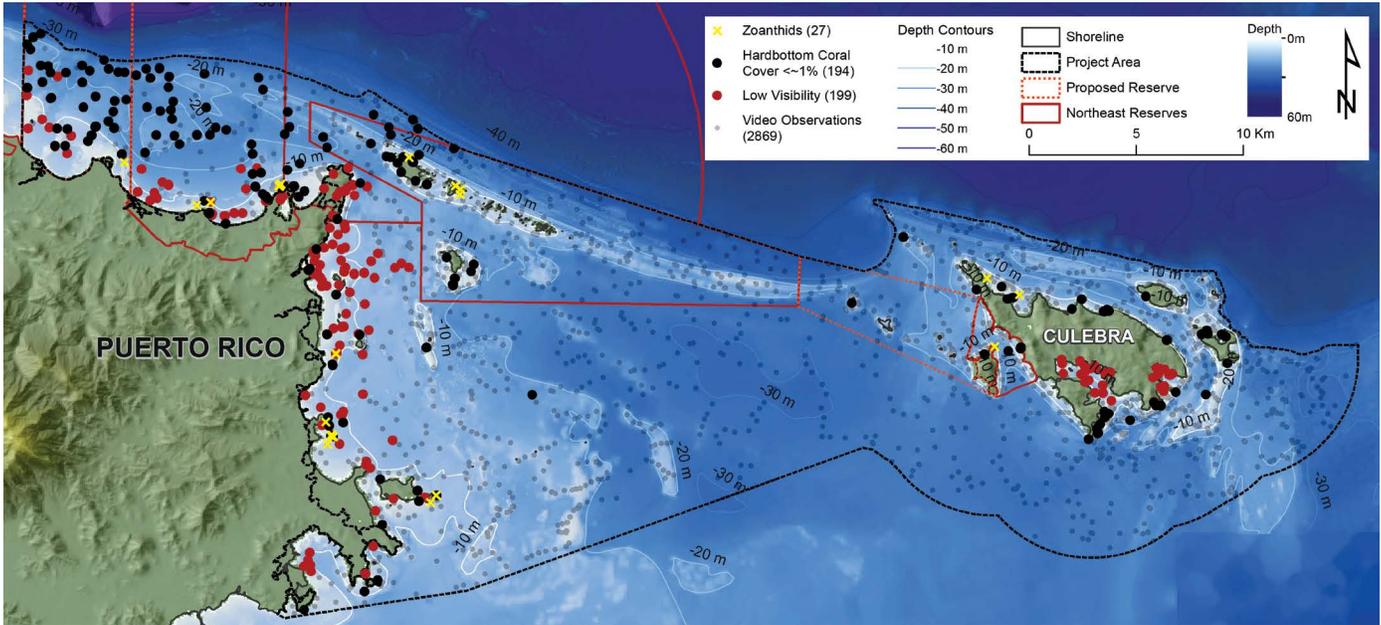


Figure 5.6. The combined observations of low visibility, reefs with low coral cover (<1%), and zoanthids (Linton and Warner, 2003) can potentially be used to help identify severely impacted reef areas.

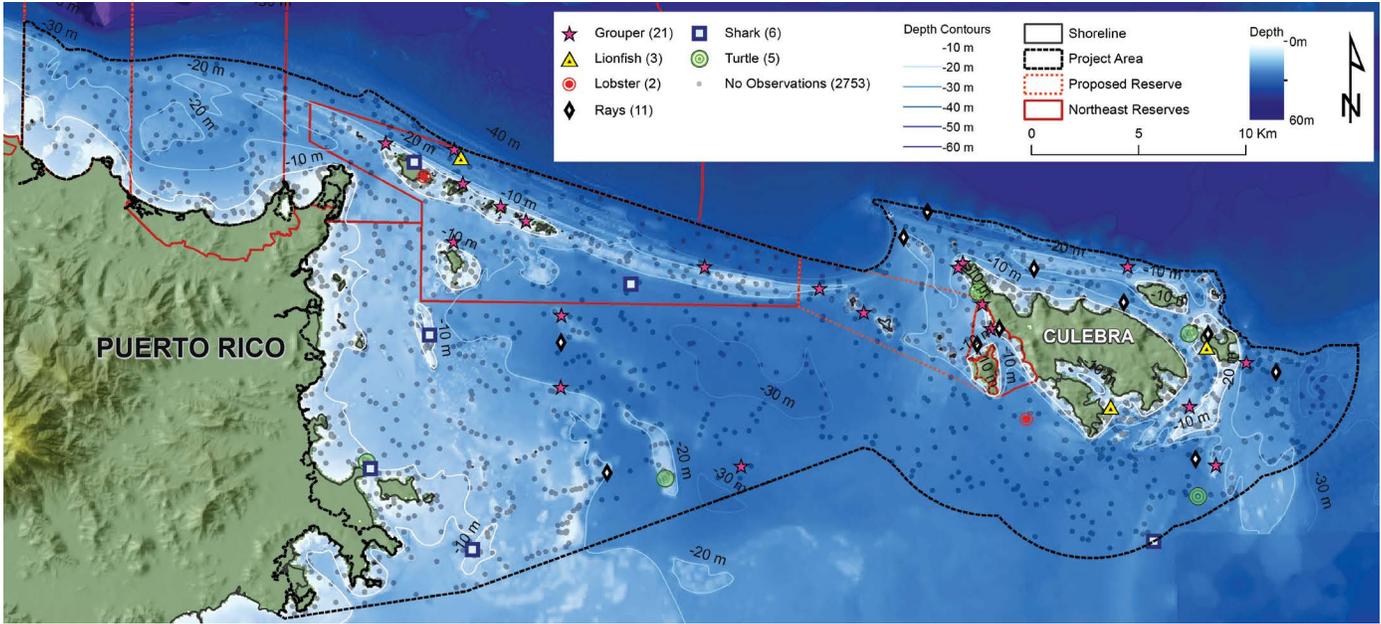


Figure 5.7. Fauna observations from underwater videos in the project area.

Benthic Habitat: Biological Cover, Percent Cover

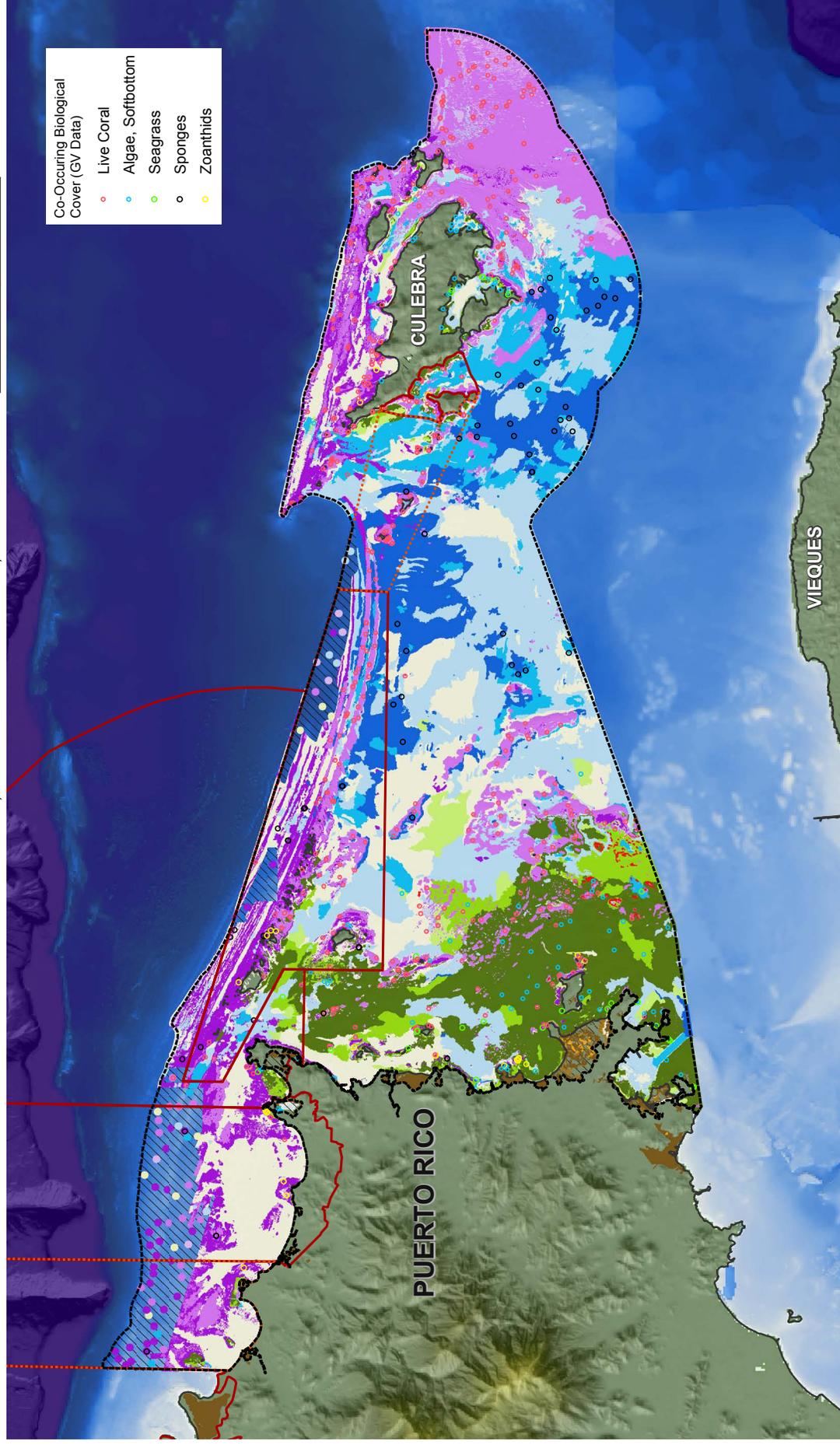
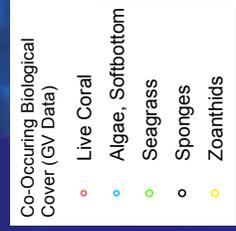
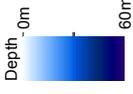
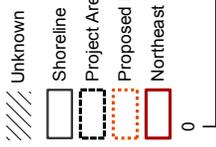


Figure 5.8. The dominant biological cover was mapped for all known hard and softbottom areas. In addition, information about co-occurring biological cover was recorded from the GV data and shown here as point data on top of the map. Examples of habitats mapped with the help of this additional category are algae dominated softbottom habitats with barrel sponges (mainly occurring together with well-formed rhodolith beds) and seagrass beds with more than 10% algae present.

Regional Trends

There are some general regional patterns that emerge from the habitat data from NEPR to Culebra Island (Figure 5.10-5.11). Generally speaking, the waters close to the mainland in the NEPR region seem to have lower visibility and lower coral cover (especially the northern part of the region) compared to the areas further east of the mainland which seem to have reefs with higher coral cover and waters with higher visibility (Figure 5.6). A few of the mapped regions stand out with relatively diverse habitats (mix of many habitat types) and high live coral cover and abundance of ESA corals one example of this kind of area is the eastern part of La Cordillera islands inside the Northeast Reserves (NE corner of the NEPR region) which contain a myriad of small islands that form protected reef areas with some larger live *Acropora* aggregations and a diversity of benthic habitats. Another example is the southeastern part of the NEPR region which, though mostly consisting of softbottom, is one of few mapped locations where live corals are the dominant biological cover on the hardbottom areas. This area is also part of the largest seagrass bed in the mapping area. Lastly, the largest extent of high relief and high coral cover reef habitat is found outside the Northeast Reserves boundaries on the east side of Culebra where clear waters and abundance of live hard coral dominated reef areas form valuable marine habitats (Figures 5.3 and 5.5).

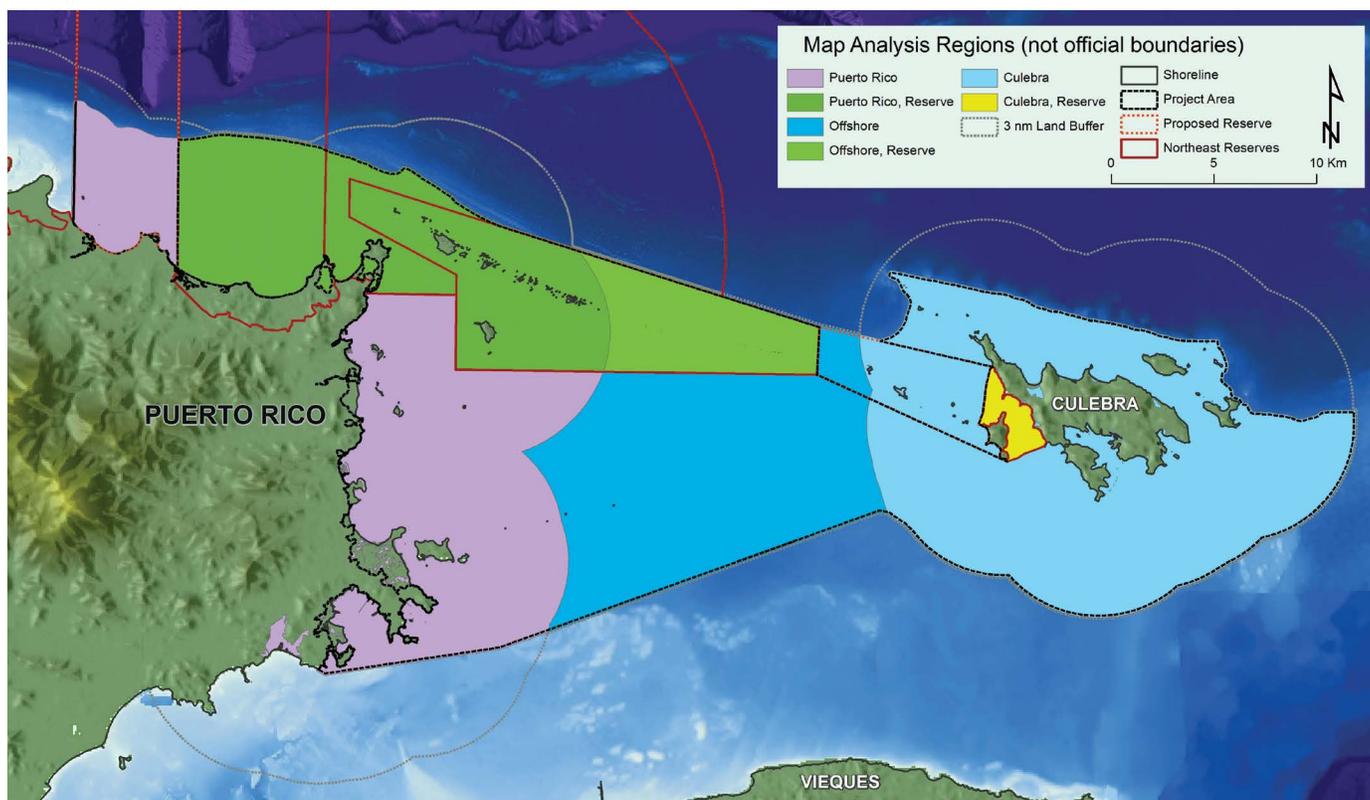


Figure 5.9. Three geographical regions were used to analyze the map data (these delineations are not part of any official boundaries and were developed specifically for this chapter): (1) NEPR - Marine habitat within 3nm from Puerto Rico mainland or any larger keys, (2) Offshore - The area between Culebra Island and Puerto Rico (sometimes referred to as Vieques Strait) outside of the 3nm land boundary, and (3) Culebra - Marine habitat within 3nm from Culebra Island or any larger keys.

Northeast Puerto Rico

The mapped area (excluding the area mapped as *Unknown*) inside the reserve boundaries (135 km², 43% of the NEPR region) is dominated by softbottom (65%). Uncolonized sand makes up 30% of the region followed by low relief reefs (20%). Moderate to high relief reefs cover 8% of the area and 5% of the area inside the Reserves was covered by seagrass (Figure 5.18). Ground validation observations in the area mapped as *Unknown* (38 km²) suggest that 80% of the area is hardbottom dominated by low relief reefs (58% of the samples were classified as *Pavement*). The GV samples and the map also show that there are large areas north of Puerto Rico where coral cover is very low (74% of the hardbottom sites in the area mapped as *Unknown* area was classified as *No Cover* for live coral) (Table 5.3). Only 13% of the mapped hardbottom inside the Reserves had coral cover higher than 10%. Hard coral (48% of mapped hardbottom areas) was the most common coral cover (Figure 5.18).

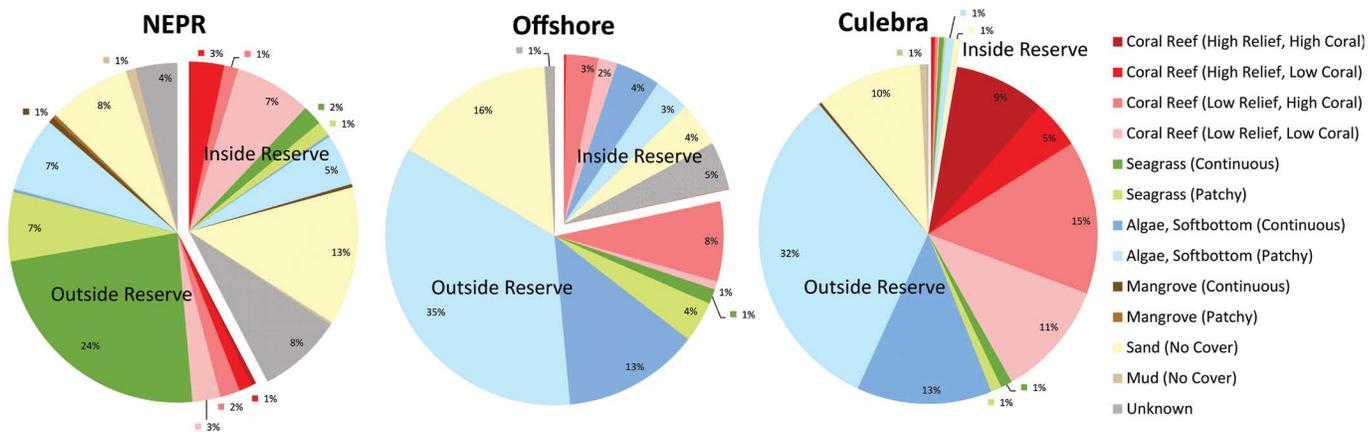


Figure 5.10. The figure shows an overview of benthic habitats inside and outside of the Northeast Reserves boundaries divided into three geographic regions (see Figure 5.9). A description of the habitat definitions can be found in Appendix A.2.

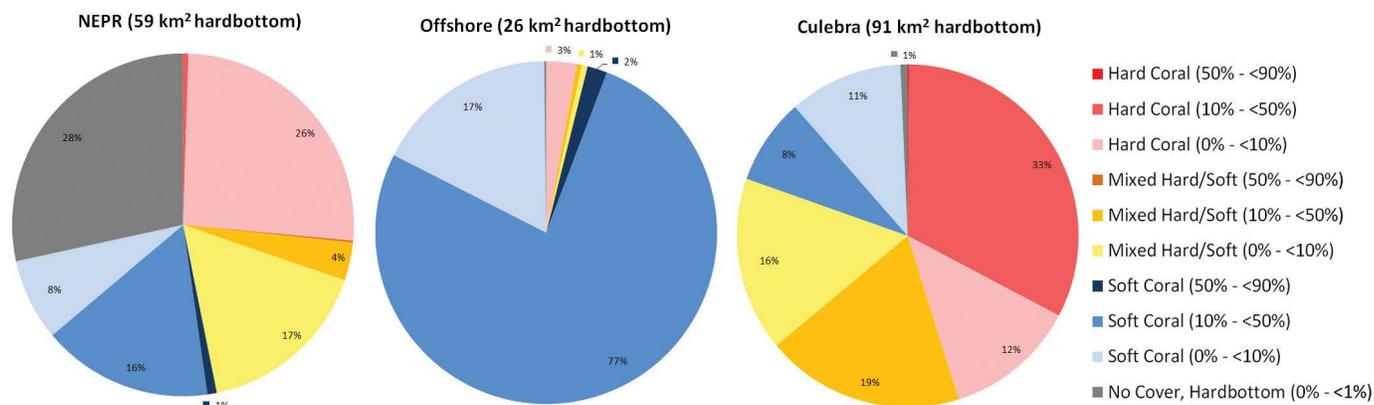
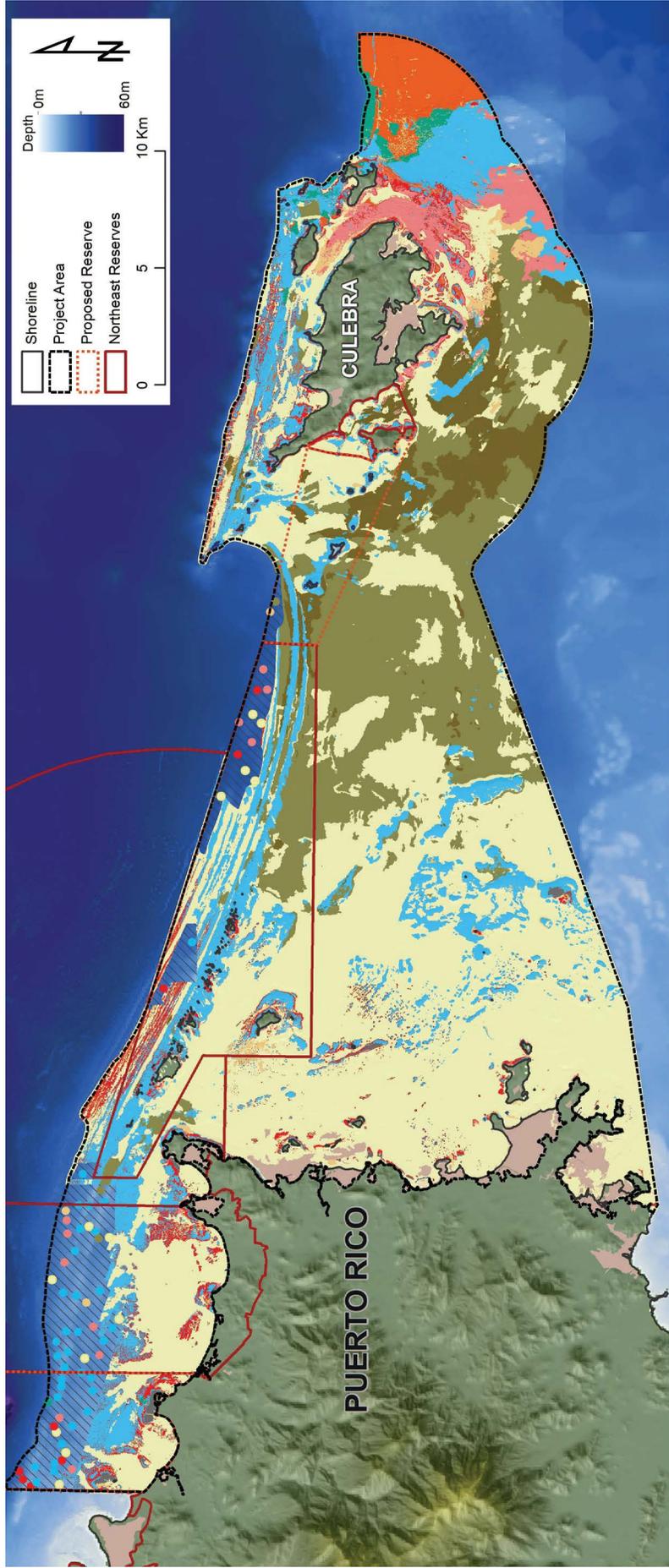


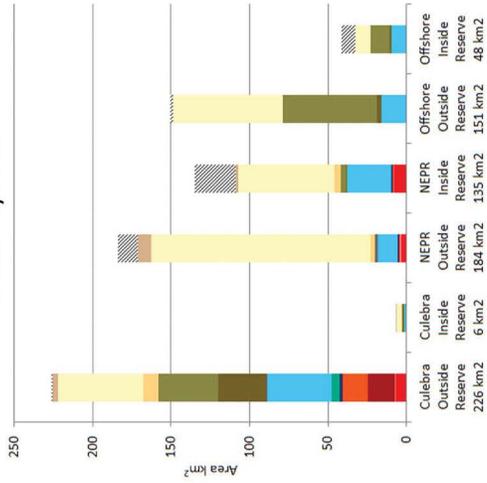
Figure 5.11. The distribution of live coral cover (percent cover and dominant coral type) on the mapped hardbottom areas divided by three geographical regions (NEPR, Offshore and Culebra, see Figure 5.9).



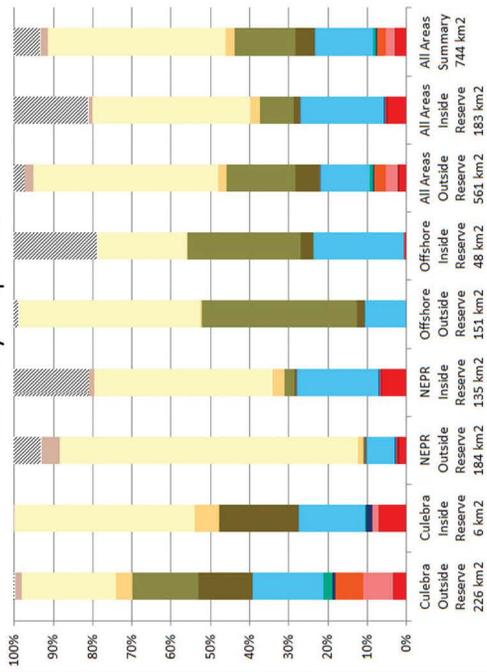
A curious Angel fish on the reef.



Habitat By Area



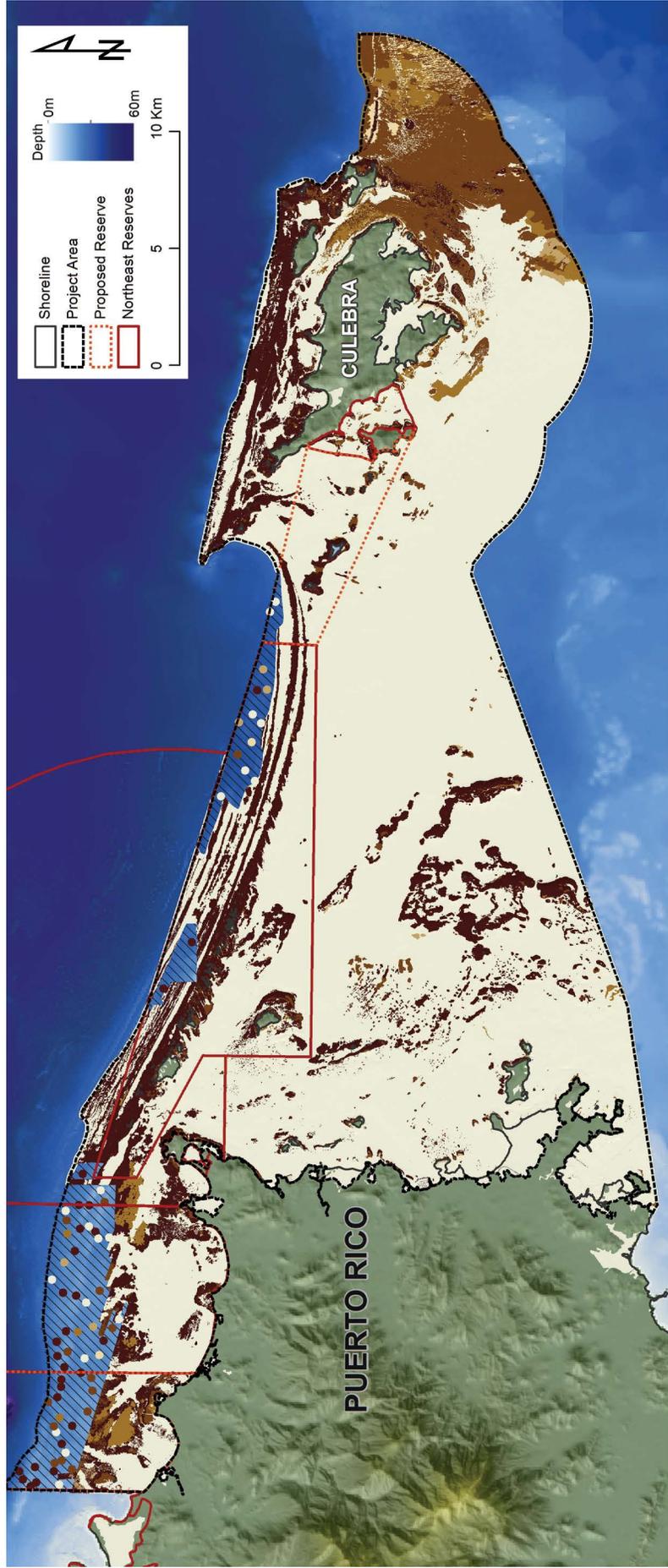
Habitat By Proportion



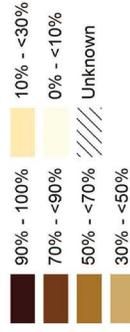
Geomorphological Structure



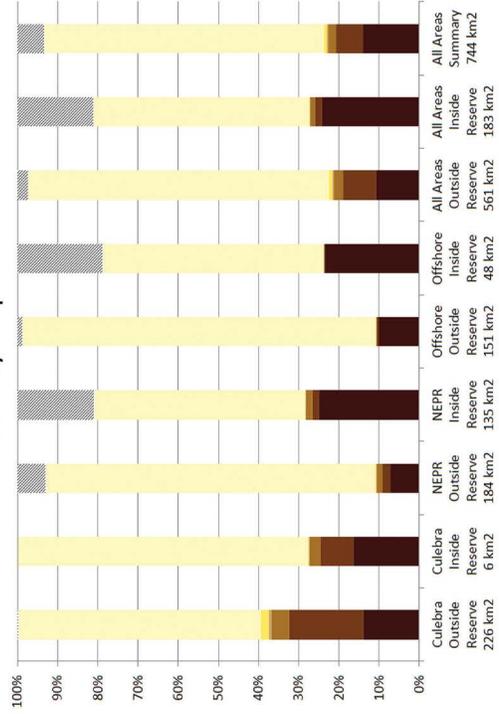
Figure 5.12. The map shows detailed geomorphological structure. The graphs show the area and distribution of geomorphological structure based on geography and the NER boundaries (Figure 5.9).



Percent Hardbottom



Habitat By Proportion



Habitat By Area

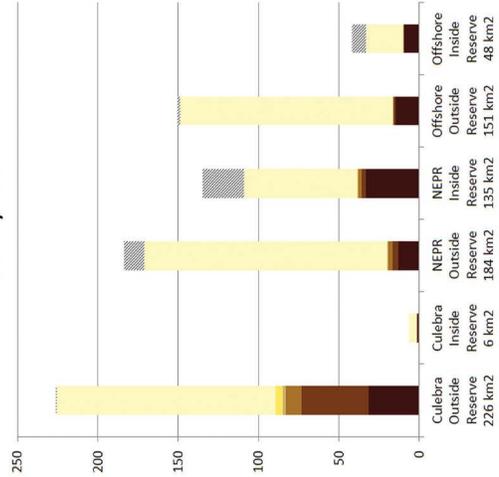
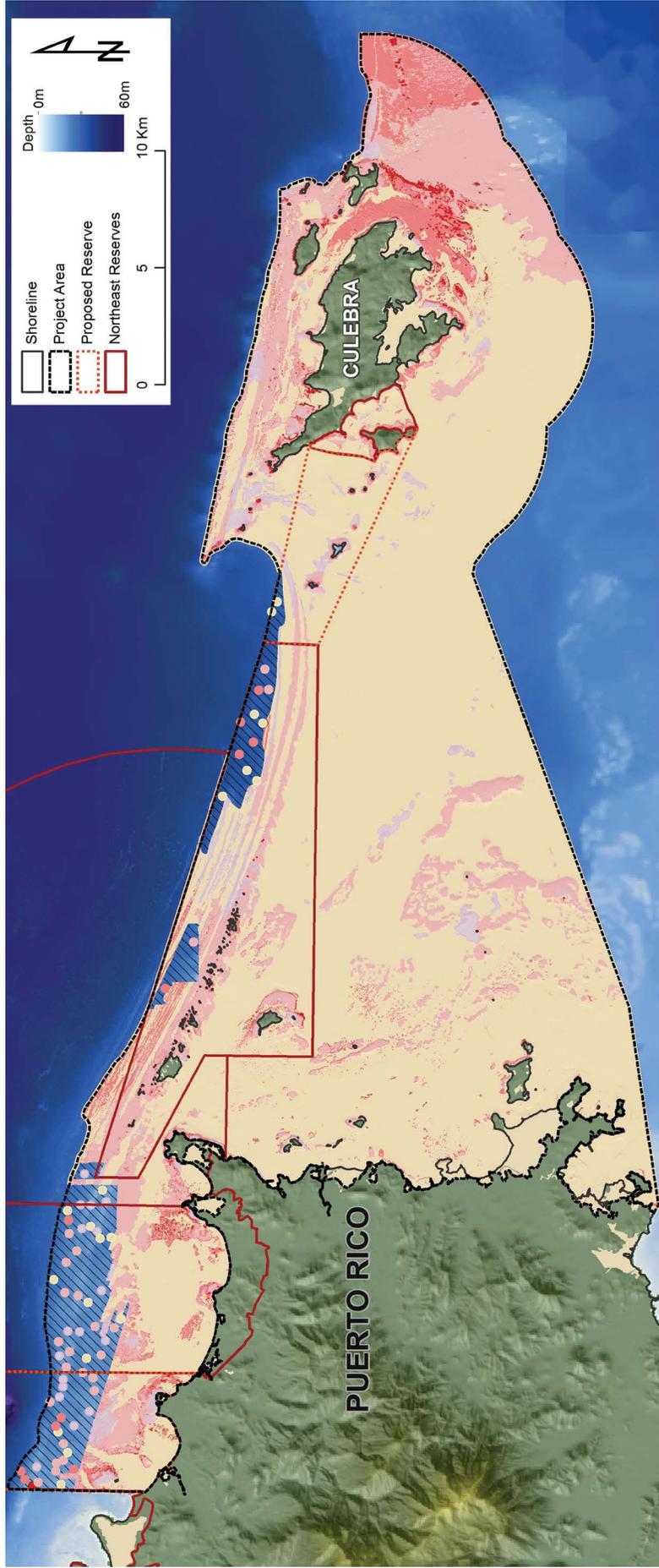


Figure 5.13. The map shows the percent cover of hardbottom habitats. The graphs show the area and distribution of hardbottom based on geography and the NER boundaries (Figure 5.9).



Topographic Complexity

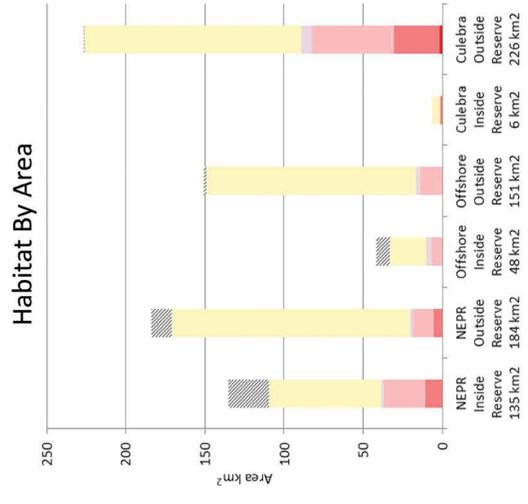
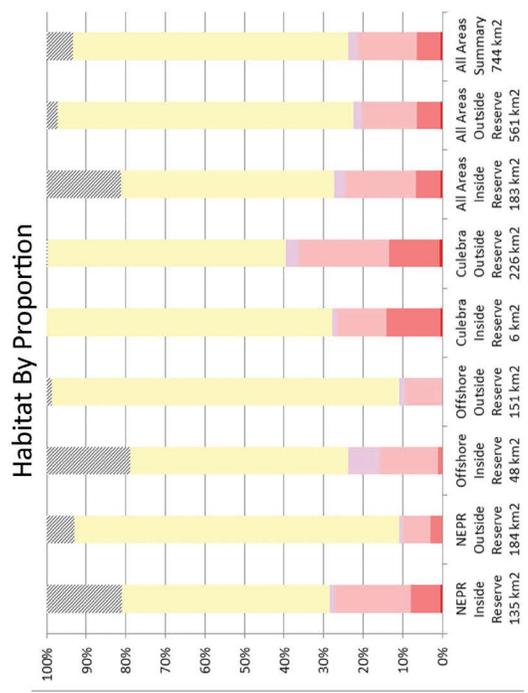
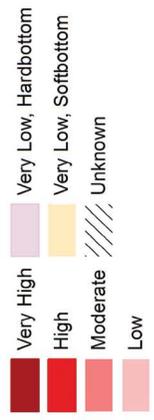


Figure 5.14. The map shows detailed geomorphological structure. The graphs show the area and distribution of geomorphological structure based on geography and the NEPR boundaries (Figure 5.9).



Major Biological Cover

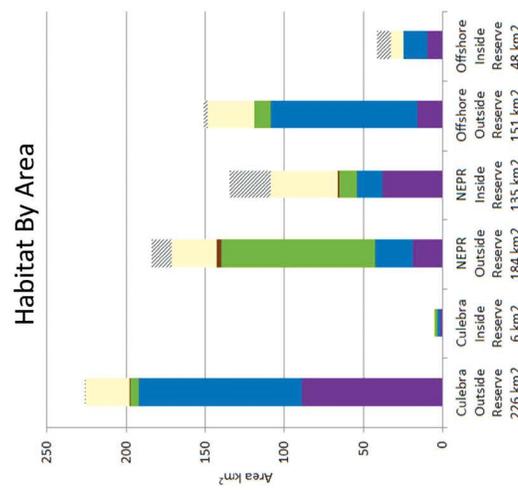
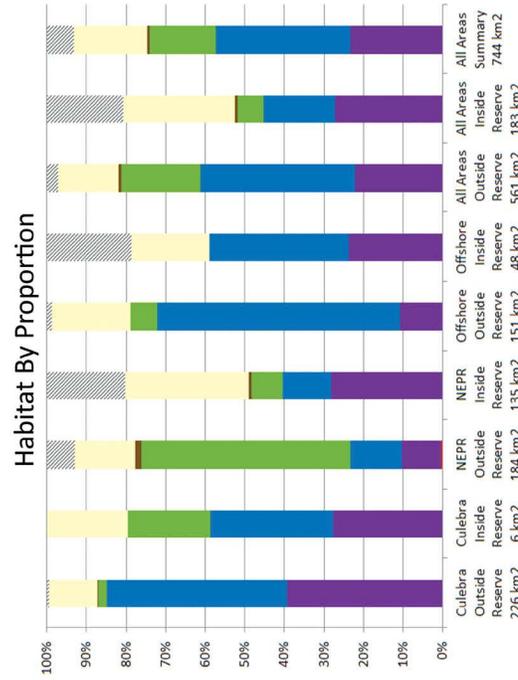


Figure 5.15. The map shows the percent cover of hardbottom based on geography and the NER boundaries (Figure 5.9).



Percent Live Coral Cover

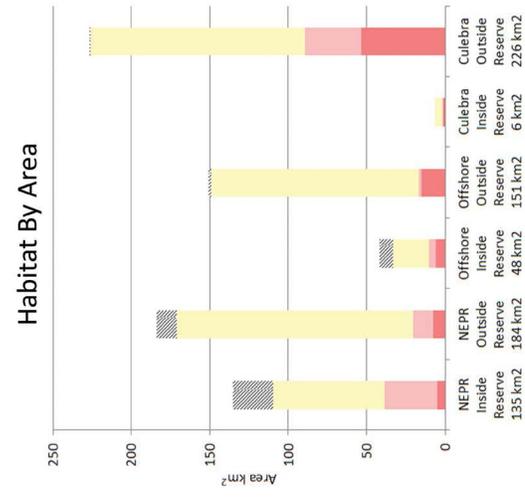
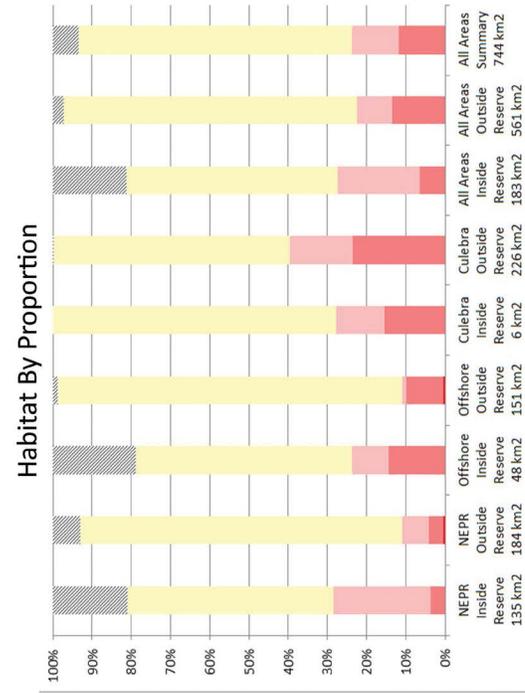
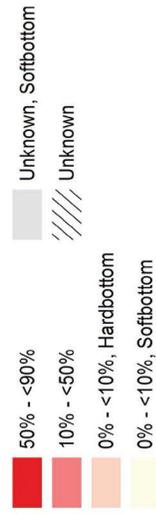


Figure 5.16. The map shows detailed geomorphological structure. The graphs show the area and distribution of geomorphological structure based on geography and the NER boundaries (Figure 5.9).



Dominant Coral Type

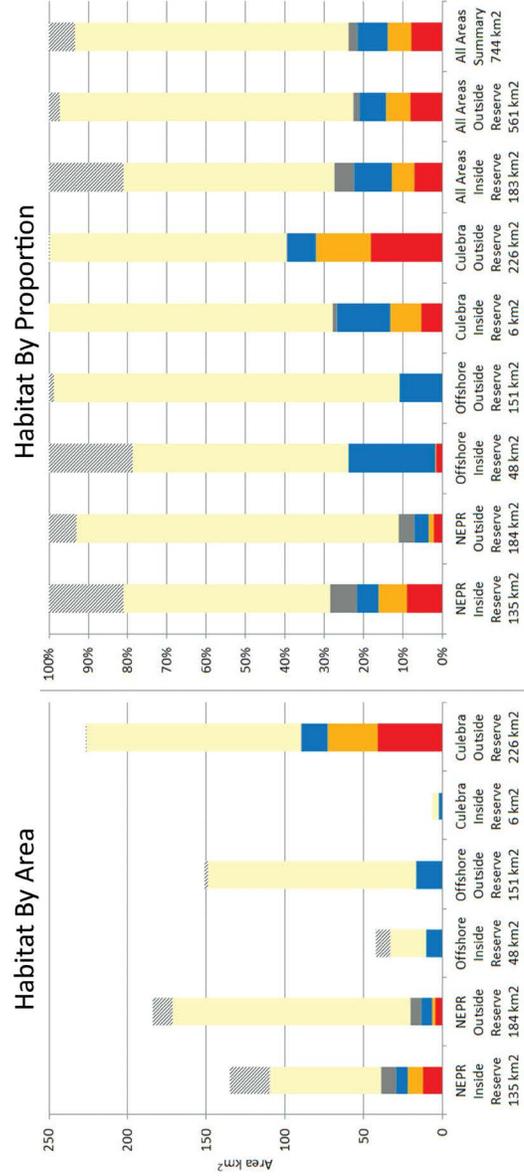
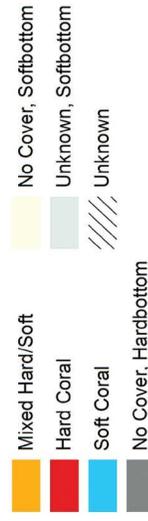


Figure 5.17. The map shows the percent cover of hardbottom habitats. The graphs show the area and distribution of hardbottom based on geography and the NER boundaries (Figure 5.9).

The mapped NEPR region outside the Northeast Reserves (184 km², 57% of the NEPR region) is dominated by softbottom (80%). Seagrass beds cover 52% of the region, followed by uncolonized sand (13%) and sand colonized by algae (12%) (Figure 5.19). Low relief coral reefs cover 8%, and moderate to high relief reefs cover 2% of the area. Live coral cover was greater than 10% for 38% of the hardbottom area. A majority of the reefs with higher coral cover than 10% were located in a soft coral dominated region in the south, which included 4% (0.6 km²) of reef areas with coral cover greater than 50%. The southeast part of the NEPR region contains a mosaic of patch reefs (5%). Although the patch reefs do not cover a big portion of the total space, they form large areas with mixed patch reef and *Seagrass* habitats. In addition there are *Mangrove* habitats (2.8 km² in total) along the southeast coast that connect spatially to the seagrass beds.

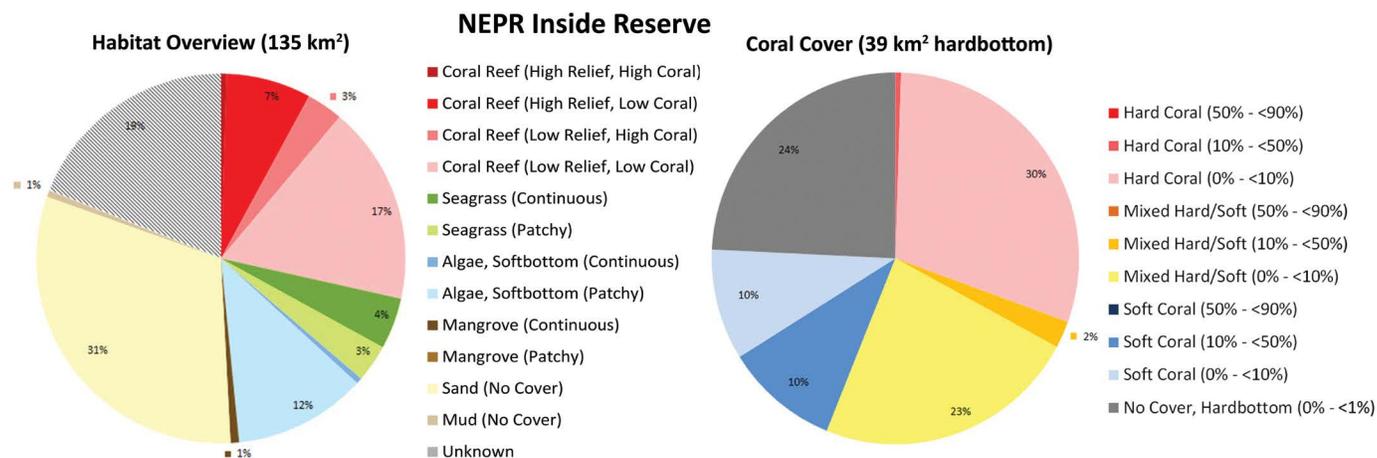


Figure 5.18. The distribution of habitats (hard and softbottom) and coral cover (hardbottom only) inside the Northeast Reserves in the region within 3 nm from Northeast Puerto Rico (Figure 5.9).

Offshore

The mapped offshore area between Culebra and Puerto Rico inside the Northeast Reserves boundaries (42 km², 21% of the offshore region) is dominated by softbottom (70%). Sand colonized by algae covers 56% of the region, followed by uncolonized sand (20%) (Figure 5.20). Low relief reefs (pavement) cover 22% while moderate to high relief reefs cover only 1% of the mapped area, though there are more coral reefs in the 11 km² (21%) deep area mapped as *Unknown* along the north side of the reserve. Ground validation data in the area mapped as *Unknown* suggest that 50% is hard bottom dominated by moderate relief reefs with low coral cover (Table 5.3). Despite the low sample size in the *Unknown* area, it is clear that the deeper waters in the northern part of the reserve contains more complex reef features than the shallower mapped area,

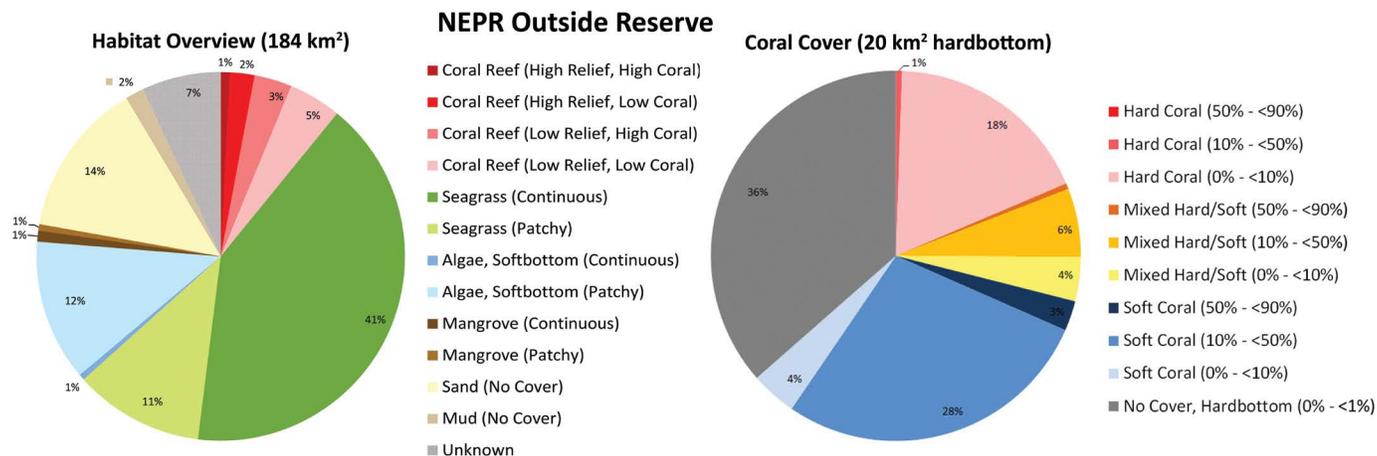


Figure 5.19. The distribution of habitats (hard and softbottom) and coral cover (hardbottom only) outside the Northeast Reserves in the region within 3 nm from Northeast Puerto Rico (Figure 5.9).

characterized by low relief reefs (mostly pavement). Fifty-eight percent of the mapped hardbottom had coral cover higher than 10%. Ninety percent of the coral cover was dominated by *Soft Corals*.

Table 5.3. GV data statistics from 59 video transects in the 49 km² combined area classified as *Unknown* in the habitat map due to insufficient remote sensing data.

Habitat	NEPR		OffShore		All Unknown	
	GV Sites	Percent	GV Sites	Percent	GV Sites	Percent
Hardbottom	47	80%	7	50%	54	74%
Softbottom	12	20%	7	50%	19	26%
Pavement	34	58%	0	0%	34	47%
Agg Reef, Patch reef	13	22%	7	50%	20	27%
Sand, Sand SCR	10	17%	6	43%	16	22%
Rhodoliths	2	3%	1	7%	3	4%
Coral, No Cover	35	74%	0	0%	35	65%
Coral, 0-10%	9	19%	7	100%	16	30%
Coral >10%	3	6%	0	0%	3	6%

The mapped offshore area outside the Northeast Reserves boundaries (151 km², 79% of the offshore region) is dominated by softbottom (89%). Softbottom colonized by algae cover 62% of the mapped area (rhodoliths made up 42% and sand 20%), followed by uncolonized sand (20%) (Figure 5.21). Low relief reefs (pavement) cover 10% and moderate to high relief reefs made up less than 1% of the area. Ninety percent of the mapped hardbottom had coral cover higher than 10% and 95% of the coral cover was dominated by *Soft Corals*.

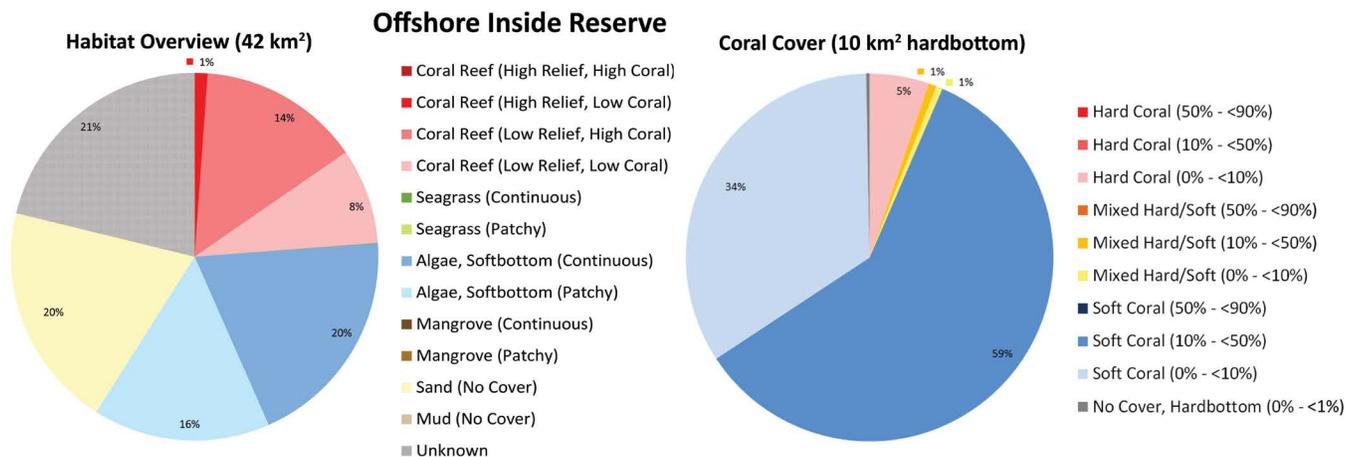


Figure 5.20. The distribution of habitats (hard and softbottom) and coral cover (hardbottom only) inside the Northeast Reserves in the offshore region between Puerto Rico mainland and Culebra Island (Figure 5.9).

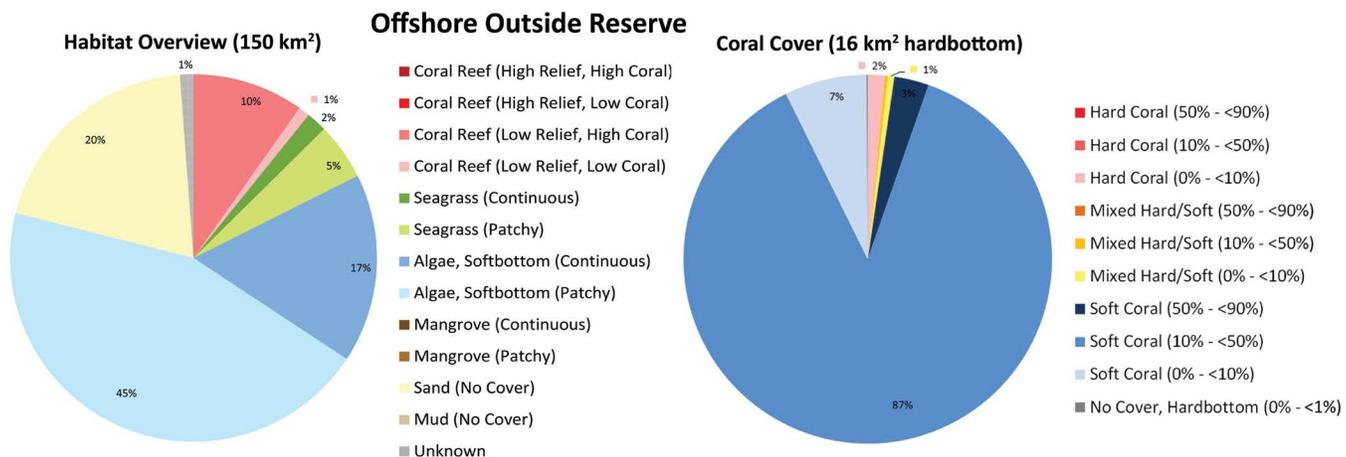


Figure 5.21. The distribution of habitats (hard and softbottom) and coral cover (hardbottom only) outside the Northeast Reserves in the offshore region between Puerto Rico mainland and Culebra Island (Figure 5.9).

Culebra

The mapped area around Culebra Island inside the Northeast Reserves boundaries (Reserva Natural Canal de Luis Peña - covering 3% (6.3 km²) of the Culebra region) is dominated by softbottom (72%). Softbottom colonized by algae (rhodoliths 20%, sand 11%) covered 31% of the mapped area, followed by seagrass (21%) and uncolonized sand (20%) (Figure 5.22). Moderate to high relief reefs, and low relief coral reefs cover 14% respectively. Over half of the hardbottom areas had coral cover greater than 10% (16% of the total area). Half of the hardbottom is dominated by soft corals (50% *Soft Corals*, 28% *Mixed Hard/Soft Corals* and 19% *Hard Corals*). Multiple observations of both *A. palmata* and *A. cervicornis* were made inside the reserves (Figure 5.5).

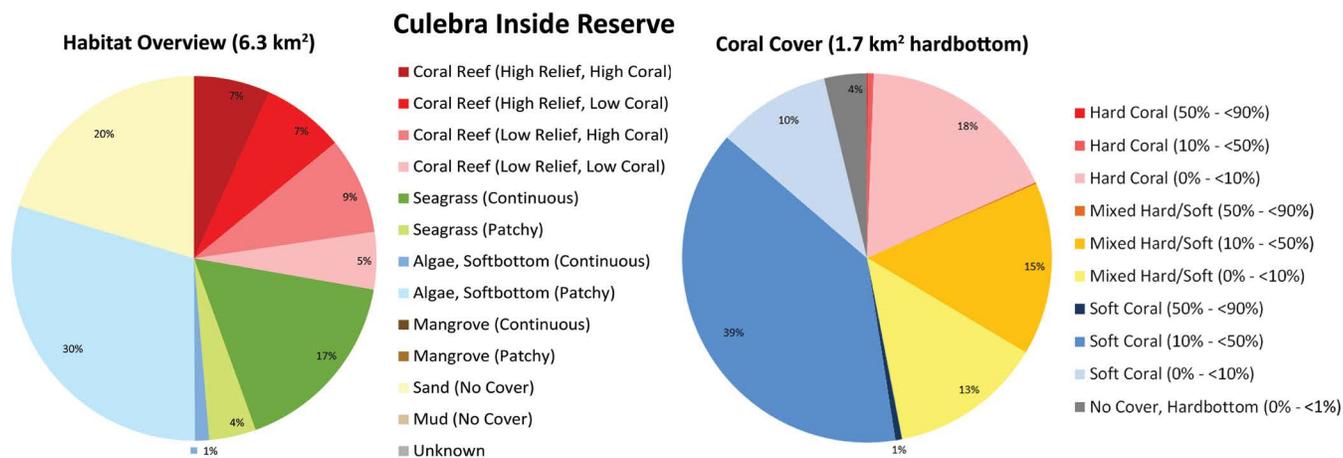


Figure 5.22. The distribution of habitats (hard and softbottom) and coral cover (hardbottom only) inside the Northeast Reserves in the region within 3 nm from Culabra island (Figure 5.9).

Ninety-seven percent (226 km²) of the mapped area around Culebra Island is outside of the reserve boundaries. This unprotected region has a majority of the coral reefs in the whole project area, in fact 90% of all moderate to high relief reefs with coral cover greater than 10% was found in this region. The mapped area around Culebra is dominated by softbottom (60%). Algae colonizing softbottom cover 46% (rhodoliths cover 31%, sand 15%) and uncolonized sand 10%, while seagrass beds cover 2% of the mapped area (Figure 5.23). Low relief reefs cover 26% while moderate to high relief reefs cover 14% of the area. A majority (60%) of the reefs had coral cover greater than 10%. Almost half of the coral cover on the reefs were dominated by hard corals (45% hard corals, 35% mixed hard/soft corals and 18% soft corals, *No Cover* was only observed for 0.6% of the hardbottom areas). Numerous observations of both *A. palmata* and *A. cervicornis* were made around the whole island, with elevated numbers for *A. palmata* on the north and west side, and elevated

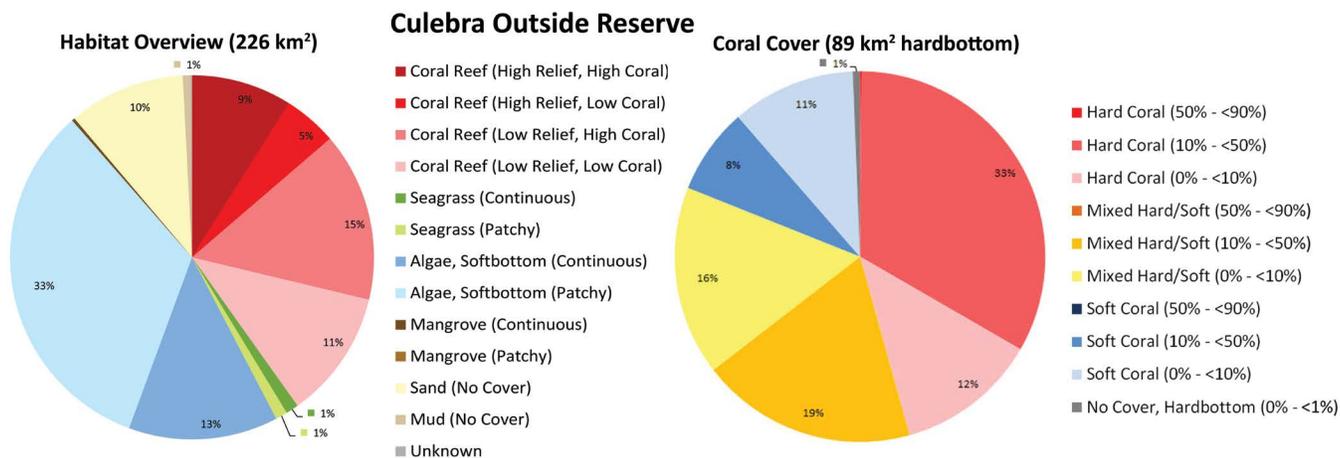


Figure 5.23. The distribution of habitats (hard and softbottom) and coral cover (hardbottom only) outside the Northeast Reserves in the region within 3 nm from Culabra island (Figure 5.9).

observations of *A. cervicornis* on the east side of the island. A majority of the reefs with high relief and high coral cover were located on the east side of the island, which included extensive deeper areas of old submerged spur and grove on the Bank/Shelf. Spur and grove made up a total of 7.2% (16 km²) of the mapped area around Culebra, which was 99.7% of all spur and groove found in the project area. Finally, the offshore area in the southwest part of the mapping region, dominated by algae and rhodoliths, consists of large areas where both corals and barrel sponges were found present in well-developed rhodolith beds (Figure 5.8).

5.2. DISCUSSION

5.2.1. Comparison to Previous Map in the Area

This mapping effort marks the second time that the shallow-water (<35 m) habitats in NEPR and Culebra have been characterized. In 2001 Kendall et al. mapped shallow coral reef habitats all around Puerto Rico and the USVI using aerial photos and GV data. There are similarities, but also differences between the old map and this new mapping effort. Essentially, the scheme that was used in 2001 evolved into the scheme used for the current map. One of the main changes is that live coral cover is now included in the scheme. The two maps are also mapped at different scales, the 2001 map has a minimum mapping unit (MMU) of 1 acre (4,046 m²) and the new map has a MMU of 100 m². Even so, the maps can be used together as long as the user is cognizant of the differences. For comparison we simplified the two maps into 10 broader habitat categories that captured similar habitats in both maps (Figure 5.24). For a crosswalk between the 2001 map and the current scheme see Table 5.3 in Costa, et al., 2013.

Coverage

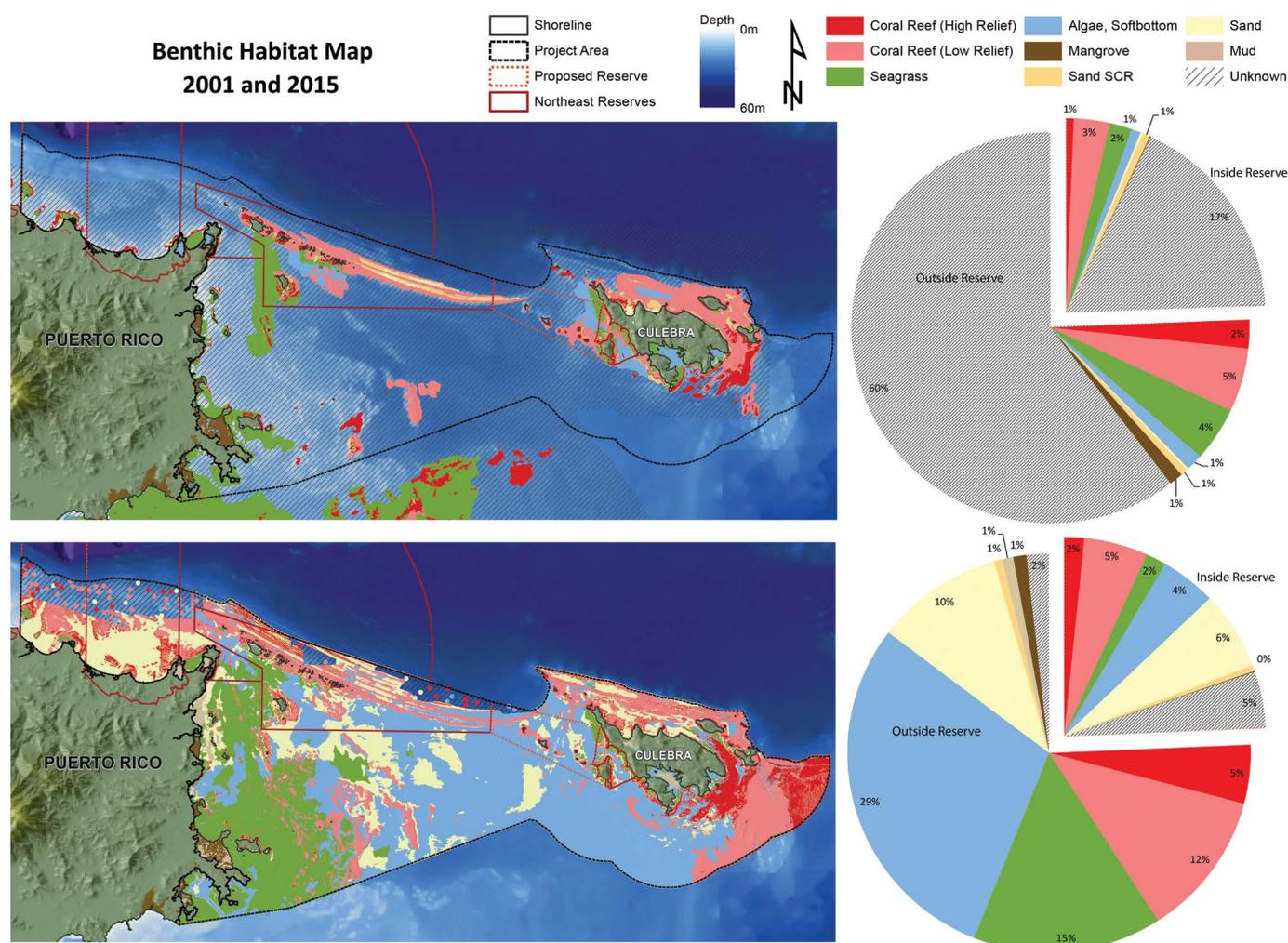


Figure 5.24. The figure shows a comparison between the new map and the old map from 2001 inside the 2015 project boundaries. The habitat attributes from the two map products was combined into 10 broader habitat categories that could be compared between the maps. The associated pie charts display the proportion of each class mapped for the two maps inside and outside the reserve.

The new map covers 545 km² of marine habitats previously classified as *Unknown* (the map from 2001 only overlapped with 22% of the new map). The effort in 2001 used aerial photos together with sparse GV data resulting in limited possibilities to characterize benthic habitats at depth if the waters were turbid or wavy. The new map uses a combination of old and new depth information together with water column corrected satellite data, in order to provide remote sensing data where depth or turbid waters hindered the previous effort from completing the map. Also, the more limited scope of this map and updated GV methods made it possible to collect and document a much more dense and rich GV data set to base the new map upon.

Thematic and Spatial Resolution

This effort used an updated classification scheme to take advantage of the higher spatial and thematic resolution made possible by feature extraction algorithms and geostatistical modelling resulting in: (1) a new classification scheme with a higher thematic resolution; (2) a finer scale of delineation; and (3) a smaller minimum mapping unit (Table 5.1). These different classification schemes, delineation scales and minimum mapping units makes it challenging to quantitatively compare the 2001 and 2015 benthic habitat maps. This sensitivity is mainly due to the size of the minimum mapping unit, which affects not only the size of habitat features delineated, but also the name that those features are given. For example, an individual patch reef that is 100 m² in size will be mapped as individual patch reef in a map with a 100 m² MMU and as aggregated patch reefs in a map with 4,046 m² MMU, or not be mapped at all if the size and density of the patch reefs are too small. These different interpretations occur because the patch reef is too small (<4,046 m²) to be characterized individually at a coarser scale. The size of the MMU also affects the rarity of a habitat class. Rare habitat classes become more common and dominant ones become less common as the size of the MMU decreases (Kendall and Miller, 2008). This occurs because habitats are delineated and classified individually at a smaller MMU instead of being aggregated with adjacent or similar habitats at a larger MMU. Notably, *Individual Patch Reefs*, pavement and sand patches often become more common when smaller MMUs are implemented.

When comparing the two maps, the mapped features in the 2001 map had a median feature size of 33,700 m² (8 times the MMU), while the new map had a median feature size of 320 m² (3 times the MMU). This would suggest that the size of features that get delineated depends on data quality and the habitat classification method in addition to the theoretical MMU used in the mapping process. An effect of this could be that a manual classification method results in a more generalized habitat map while a semi-automated classification method results in a more detailed map when the same MMU is used.

5.2.2. The New Habitat Classes

Two new attributes (*Topographic Complexity*) and (*Dominant Coral Cover*) were added to the Biogeography Habitat Classification Scheme compared with the most recent habitat map implementations (Bauer, et al. (2012); (Costa, et al., 2013)). The use of these two classes and the results are evaluated below.

Topographic Complexity

Topographic Complexity was estimated from underwater video imagery then modelled across the mapping area using several spatial predictors (Table 3.5 (pg. 57)). Seascape ecology studies indicate that *Topographic Complexity* is one of the major environmental drivers for fish distribution and diversity across the seascape (Pittman, et al., 2010). In the previous implementations of the biogeography classification scheme, rudimentary distinctions between reefs with high complexity and reefs with low complexity were made by separating *Reef Rubble*, *Pavement*, and *Pavement With Sand Channels* (~very low-low complexity) from *Aggregate Reef*, *Spur and Groove*, *Aggregated Patch Reefs*, and *Patch Reefs* (~low-high complexity). However, there was no measure of how complexity changes within the same structure class. For example: a reef wall with undercuts and rugose hard coral structures and a flattened low complexity *Aggregate Reef* with little remaining structure could both be classified as an *Aggregate Reef* with the same habitat attributes (Figure 5.25). Traditionally seascape ecology studies of reef complexity have relied predominantly on high resolution bathymetry models to provide a measure of reef complexity. With consistent and high resolution depth data

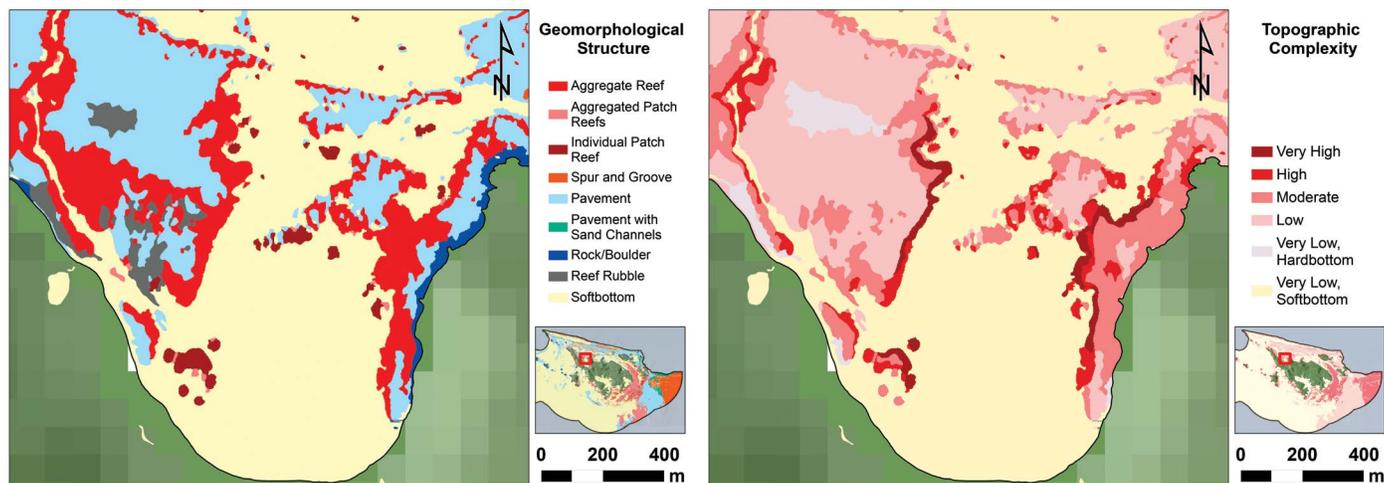


Figure 5.25. The figure shows a map comparison between detailed geomorphological structure (left) and topographic complexity (right) for the reefs around the popular Flamenco Beach in Culebra. Notice that without the topographic complexity information there is no information in the structure class to separate a highly complex reef from a low-moderate complex reef.

this has been shown to be an effective approach (Pittman, et al., 2009, 2010). In the NEPR mapping area the density of available depth soundings varied between 4 meters and 200 meters, which makes consistent *Topographic Complexity* studies very challenging. However, since the *Topographic Complexity* habitat class was based on video observations and a range of spatial predictors it enabled us to provide a measure of topographic complexity across the multi-resolution depth model (Figure 5.26). A combination of the habitat map measure of topographic complexity and the direct measure (such as rugosity) using available depth data in regions with high quality depth data will likely result in a more robust and complete picture of the topographic variations in the mapping area.

One of the main difficulties in mapping *Topographic Complexity* during this study has been to derive an accurate and consistent measure of complexity from visual classifications of the video imagery, and to stay consistent between multiple analysts (a common problem for all habitat mapping efforts). Future implementations of this approach would likely benefit greatly if a quantitative measure could be used by creating high resolution digital terrain models directly from the ground validation imagery. The advancement of SfM (Structure from Motion) techniques have greatly increased the possibility of using underwater video cameras to capture coral reef complexity at centimeter scale resolution (González Rivero, et al., 2014; He, et al., 2012; Lavy, et al., 2014; Leon, et al., 2015). This would allow for quantitative standardized values of complexity/rugosity to be derived from each video transect, thereby increasing both accuracy and thematic resolution of this class. In such a scenario complexity might be better modelled using a continuous raster

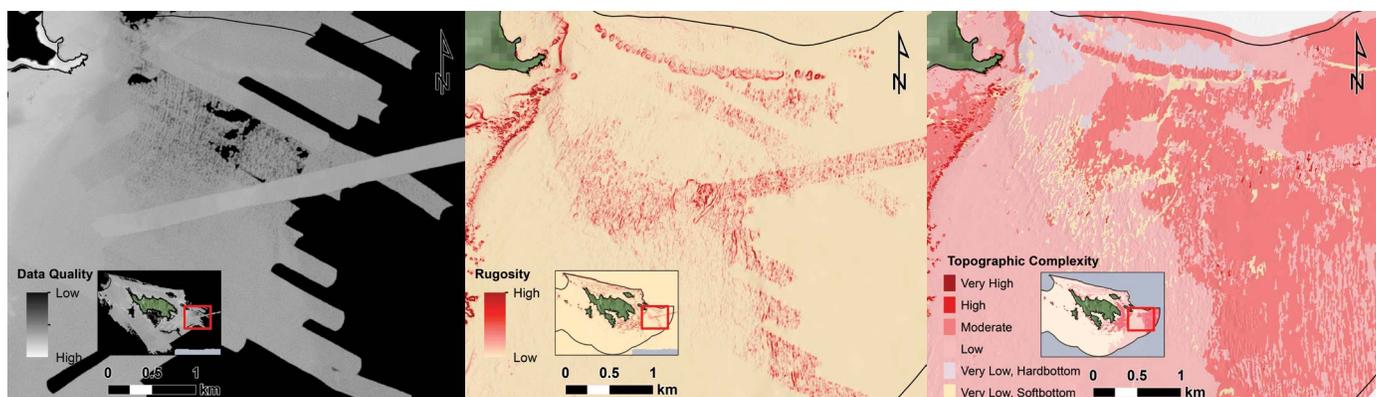


Figure 5.26. Rugosity show the uncertainty of the bathymetry model (left), the rugosity value derived from the same bathymetry model (middle), and the mapped topographic complexity based on underwater video observations (right). Notice how the rugosity value depends on data quality (a mix of high resolution multibeam data, Lidar data and historical hydrographic data), while the mapped topographic complexity show less correlation with the quality of the depth data, and characterize large areas as moderate complexity that are not visible in the bathymetry data.

rather than a feature extraction approach confined to a minimum mapping unit. A quantitative complexity measurement could also help define and interpret the geomorphological structure classes more precisely. Hardbottom structure classes can be challenging to classify since the exact delineation between, for example, pavement habitats versus other reef types depends on the analyst interpretation of reef complexity.

Live Coral Cover

Dominant coral cover was estimated from the underwater videos to provide a modifier to separate reefs dominated by soft corals from reefs dominated by hard corals. This approach has been tested in the USVI with some success for reefs with coral cover greater than 10% (Costa, et al., 2013). In this mapping effort we included all reefs regardless of the amount of coral cover. Reefs with less than approximately 1% coral cover were classified as *No Cover*, while reefs with 1-100% cover were classified as *Soft Coral*, *Mixed Hard/Soft Coral* or *Hard Coral*.

Even though the accuracy of live coral cover estimates on the MMU scale is challenging in complex reef areas, the mapping effort was able to distinguish among large sections dominated by hard or soft corals and revealed broad-scaled patterns in coral cover across the mapping area. The map also captured a large region consisting of reefs with coral type mapped as *No Cover*. These regional scale patterns should provide important and reliable information to managers and scientists alike, even if caution is needed for analysis at the scale of the MMU. A closer look at the accuracy assessment (chapter 4) for dominant coral cover shows that there was a number of false classifications between soft and hard corals versus the mixed class, while there was no mix up between hard versus soft corals directly. The accuracy assessment for the *No Cover* hardbottom class remained inconclusive since the AA did not cover the major region where this class occurred.

The current baseline for coral cover in the Caribbean has shifted downward from its historical record. The average coral cover (based on in situ data, and not directly comparable to the habitat map coral cover) for



Elkhorn coral.

nearby Vieques Island has changed from 42.6% (surveyed 1970-1983) to 12.6% (surveyed from 1999-2011), while the overall average coral cover for the wider Caribbean region has changed from 34.8% (1970-1983) to 16.8% (1999-2011) (Jackson, et al., 2014). With the new baseline around 15% coral cover, the current classification scheme (combining 0% to 10% coral cover, and 10% to 50% coral cover) is limited in its ability to accurately map trends of coral cover at the scale of the current baseline. A future development of this class could be to map soft corals and hard coral cover separately, and with a continuous variable (0-100%) in each GV image (for example soft coral 7%, hard coral 13%, and total live coral cover 20%). This would likely be an advantage for predictive modelling since a continuous variable could be used. It could also result in a more accurate measure of map accuracy since the class threshold effect would be avoided (coral cover in the mapped area often varied very close to the 10% cover threshold, making map accuracy estimates challenging). In order to map corals with a continuous variable (0-100%), at a reasonable level of effort, new methods need to be developed for GV data classification. One method currently under development is to employ random point annotations on downward looking high quality images of the seafloor, then use computer vision techniques to speed up the classification process (Beijbom, et al., 2012; González Rivero, et al., 2014). The annotated point statistics could then be used to calculate coral cover, biological cover and percent hardbottom cover.

5.2.3. Additional Field Data Information

Observations of fauna, ESA corals, biological cover and water visibility were extracted from the ground validation and accuracy assessment videos to provide additional information to the ongoing ecological assessment project for the Northeast Reserves. The GV sites were placed to optimize the verification of features identified in the remote sensing imagery. The AA sites, on the other hand, were selected using stratified random sampling based on the draft habitat map. The non-random site selection for the GV data is one of the main limitations of this dataset. Another limitation is the limited view of the underwater video camera and the relative short duration of most observations (1-3 minutes), something to carefully consider when interpreting what an “absence” of a species/habitat means (the species/habitat could have been present just outside the camera view).

The additional time commitment for the extended data extraction was relatively small, and the benefit of integrating these observations with habitat mapping efforts should be tremendous as opposed to deploying a separate field mission. However, the time associated with defining, documenting and finalizing these additional products can be substantial and should not be underestimated in future efforts.

Future additions to ecological observations from high quality underwater imagery could include adding the five species of ESA listed Caribbean corals that were listed in 2014 (*Mycetophyllia ferox*, *Dendrogyra cylindrus*, *Orbicella annularis*, *Orbicella faveolata*, and *Orbicella franksi*). Another potential development is to improve visibility by equipping the underwater camera with a photometer and a depth sensor to directly measure the light attenuation at depth.

5.2.4. Conclusions and Suggestions for Future Mapping Efforts

This project resulted in the creation of a very detailed habitat map (MMU 100 m²) that covers an area approximately 10 times larger than similar previous mapping efforts by the NCCOS Biogeography Branch, and mapped areas that were previously unmapped gaps (79 % of the project area was previously mapped as *Unknown*). The mapping approach incorporated multiple sources of remote sensing imagery and predictor variables together with a rich ground validation data set, which made the mapping approach robust even as individual data layers shifted in resolution and quality. The resulting fine scale level habitat map provides detailed information on the complex composition of coral reef ecosystems in a standardized repeatable way, and enabled the documentation of small features such as ecologically important patch reefs <1,000 m² that otherwise would have been classified as sand if mapped at coarser scale levels.

The tools developed in this project have enabled high resolution habitat mapping in areas where data quality affected the output of habitat maps. Modelled after this mapping effort, large areas such as the whole coast

of Puerto Rico could be mapped using a combination of high resolution satellite imagery, oceanographic models and existing depth data. In order to map such large areas (order of 10,000 km²) at high spatial resolution the habitat classification scheme would likely have to be adjusted and simplified, as the possibilities to effectively manually edit the map would be limited. In addition, a substantial effort to collect standardized ground validation data would have to be made. Future habitat mapping projects should consider extending the current habitat map to cover a 290 km² area of shallow water habitats south of the project boundary. This area is already covered by the remote sensing imagery developed for this project, and with additional collection of GV data this area could be mapped with existing imagery.

Limitations and Challenges of Fine Scale Habitat Mapping Over Large Areas

Increasing the mapping area, while maintaining thematic and spatial resolution, involves a number of challenges. A major challenge was the size and scale of the mapping area (orders of 1,000 km²) compared with previous attempts (order of 100 km²), which required that the semi-automated approach (Costa and Battista, 2013) become more automated due to the tenfold increase in cost and effort to reclassify the map manually. When comparing the accuracy of the model map and the manually edited/improved map that not all classes improved after the manual edits (Table 5.4 and Table 3.6 (pg. 59)). This indicates that final map accuracy is limited by other factors as well (such as data quality and resolution). However, manual editing was found especially important in regions with poor data quality regions where other data sources, such as high resolution aerial imagery from multiple sources, had to be incorporated to create an accurate map. The size of the project area also limited the ability to collect ground validation sites at high density. Compared with previous similar projects (Costa, et al., 2012, 2013), this effort used ~75% lower density of GV sites (2 sites/km² compared with 8 sites/km²). The lower density of GV sites likely had a negative impact on final map accuracy, though the impact was reduced by the overall greater number of sites.

Table 5.4. The table shows a comparison between the overall accuracy of the unedited model versus the manually edited map (described in Chapter 4). For some classes, such as detailed geomorphological structure, manual editing did not improve the overall accuracy as measured by the independent accuracy assessment team. See Table 3.6 (pg. 59) in Chapter 3 for estimated numbers of manually edited polygons for each class.

Class	Model AA	Map AA
Major G. Structure	89.1%	90.8%
Detailed G. Structure	63.9%	63.4%
% Hardbottom	72.8%	74.9%
T Complexity	68.1%	71.2%
Biological Cover	85.8%	87.6%
% Coral Cover	69.9%	70.3%
Dominant Coral Type	71.8%	72.3%

Effective manual editing of semi-automated generated maps covering large areas is challenging since the maps are very detailed. During this mapping effort we limited the MMU to 1,000 m² to enable more time efficient manual edits. However, we found that changing the MMU of the computer generated and classified segments from 100 m² to 1,000 m² which resulted in significantly lower map accuracy, as well as the loss of large numbers of patchy hardbottom features (<1,000 m²). Part of the difficulty with using a larger MMU was in connecting the scale of habitats captured by the segmented remote sensing imagery with the scale of habitats observed from the GV data. In many areas, the analyst only had reliable information from the GV data to classify a site (due to low quality and resolution of available remote sensing imagery), which was then used to train the habitat models.

An alternative to further automating the mapping process (in order to capture larger areas at high resolution) is to create maps manually. This have been done successfully in the past (Kendall, et al., 2001) and has provided valuable habitat information to managers and scientists alike. Though manual habitat mapping can cover very large areas in a time effective manner, the products are often limited to substantially lower spatial and thematic resolution.

Suggestions for Future Large Scale Mapping Efforts

The experiences from this project indicate that some adjustments to the benthic habitat classification scheme could improve the semi-automated mapping approach and enable more time efficient habitat mapping over large areas, while maintaining or improving map accuracy. One such modification could be to simplify the classification scheme by removing the zone aspect, so that all habitats can be identified directly from underwater video without the support of remote sensing data. This would simplify the process of training computer

models and would also allow for computer vision techniques (Beijbom, et al., 2012; González Rivero, et al., 2014; Krizhevsky, et al., 2012) to assist in classifying the GV data (manual interpretations are both subjective and time consuming for large data set >1,000 videos). A computer vision based approach for interpreting GV data would likely also benefit from using continuous variables for cover modifiers (such as coral cover), instead of categorical class definitions.

5.3. MAP USES

In the past, scientific and management communities have used NOAA benthic habitat maps to structure monitoring programs, support management decisions, as well as to establish and manage marine conservation areas (Friedlander et al. 2007; Pittman et al. 2008; Bauer et al. 2010; Pittman et al. 2010; Whittall et al. 2011). The habitat map and extensive field observations created during this effort can be used for similar applications, provided that the classification scheme and MMU of this map are taken into consideration during the analysis. In addition to these applications, several additional research and management applications may be possible using the bathymetry, satellite mosaic field observations and benthic habitat maps developed during this project. These additional applications may include, but are not limited to:

- Updating the management plan of the Northeast Reserves (NER), including evaluating different zoning options for multiple use areas.
- Evaluating the efficacy of management actions in the NER.
- Helping to inform and direct any restoration and conservation efforts made possible by the recent Habitat Blueprint designation to the region.
- Predicting habitat suitability for priority species (including ESA species) to guide monitoring and restoration efforts and help identify threats and prioritize protection.
- Mapping ecosystem services and estimating economic value of goods and services across the seascape.
- Understanding the seascape requirements for species and identifying the most productive and diverse seascape types.
- Understanding the importance of seafloor complexity as a driver of faunal distribution and diversity
- Development of 3D visualizations of the seascapes around NEPR and Culebra for outreach purposes.

Looking forward, these map applications may help scientists and managers to better understand the benthic communities and to help identify ecologically important areas. This knowledge is vital to help restore and protect these valuable ecosystems from current and future threats.



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Appendix A.1. Habitat Classes By Region

Classification Attribute	NEPR Inside Reserve		NEPR Outside Reserve		Offshore Inside Reserve		Offshore Outside Reserve		Culebra Inside Reserve		Culebra Outside Reserve		All Areas Inside Reserve		All Areas Outside Reserve		All Areas Summary			
	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%		
Total Mapped Area	135.0	42.3	183.9	57.7	41.7	21.7	150.7	78.3	6.3	2.7	226.4	97.3	183.0	24.6	561.0	75.4	744	100		
Land	Shoreline length (km)		47.8		100.9	39.9	0.9	0.3	0.2	0.1	11	4.5	91.7	36.3	60	23.7	193	76.3	253	
	Connected Islands		97		31		12		2		2		69		111		102		210	
Major Structure	Coral Reef and Hardbottom		38.5	28.5	20.0	10.9	9.9	23.8	16.3	10.8	1.7	27.7	89.4	39.5	50.1	6.7	125.7	16.9	175.9	23.6
	Unconsolidated Sediments		70.9	64.8	151.2	88.2	23.0	69.8	132.7	89.1	4.5	72.3	136.6	60.4	98.4	13.2	420.4	56.5	518.8	69.7
	Unknown		25.6	12.5	12.8	3.8	8.8	13.7	1.8	0.6	0	0	0.34	0.1	34.5	4.6	14.9	2.0	49.4	6.6
Geomorphological Structure	Artificial		0.0	0.0	0.1	0.1	0.00	0.0	0.00	0.0	0.00	0.0	0.0	0.001	0.0	0.12	0.0	0.12	0.0	
	Aggregate Reef		8.4	6.3	3.5	1.9	0.27	0.7	0.15	0.1	0.43	6.9	7.2	3.2	9.1	1.2	10.8	1.5	19.9	2.7
	Aggregated Patch Reefs		0.3	0.2	0.4	0.2	0	0	0.002	0.0	0.11	1.7	17.2	7.6	0.41	0.1	17.6	2.4	18.1	2.4
	Individual Patch Reef		0.57	0.4	1.1	0.6	0.05	0.1	0.002	0.0	0.01	0.2	0.67	0.3	0.64	0.1	1.8	0.2	2.5	0.3
	Spur and Groove		0.02	0.0	0.02	0.0	0	0	0	0	0.002	0.03	16.2	7.2	0.02	0.0	16.2	2.2	16.2	2.2
	Rock/Boulder		0.37	0.3	0.39	0.2	0	0	0	0	0.09	1.5	1.7	0.8	0.46	0.1	2.1	0.3	2.6	0.3
	Pavement		28.2	20.9	13.0	7.1	9.6	23.0	15.9	10.5	1.1	16.9	40.8	18.0	38.8	5.2	69.7	9.4	108.6	14.6
	Pavement with Sand Channels		0.04	0.0	0.06	0.0	0	0	0.01	0.0	0.02	0.3	5.19	2.3	0.06	0.0	5.3	0.7	5.3	0.7
	Reef Rubble		0.55	0.4	1.4	0.8	0	0	0.27	0.2	0.01	0.1	0.5	0.2	0.56	0.1	2.2	0.3	2.8	0.4
	Rhodoliths		3.5	2.6	0.28	0.2	12.0	28.8	59.8	39.7	0	0	38.2	16.9	15.5	2.1	98.3	13.2	113.8	15.3
	Rhodoliths with Scattered Coral and Rock		0.10	0.1	0.06	0.0	1.4	3.2	2.8	1.9	1.3	20.0	30.7	13.6	2.7	0.4	33.6	4.5	36.3	4.9
	Sand		61.4	45.5	139.8	76.0	9.4	22.6	69.7	46.2	2.9	45.9	54.6	24.1	73.7	9.9	264.1	35.5	337.7	45.4
	Sand with Scattered Coral and Rock		4.1	3.8	2.6	1.5	0.14	0.4	0.40	0.3	0.40	6.38	9.5	4.2	4.7	0.6	12.5	1.7	17.2	2.3
	Mud		1.8	1.3	8.3	4.5	0	0	0	0	0	0	3.6	1.6	1.8	0.2	12.0	1.6	13.7	1.8
Unknown		25.6	19.0	12.8	6.9	8.8	21.2	1.8	1.2	0	0	0.34	0.2	34.5	4.6	14.9	2.0	49.4	6.6	
Percent Hardbottom	0% - <10%		70.9	52.5	151.2	82.1	23.0	55.0	132.7	88.0	4.5	72.3	136.6	60.3	98.4	13.2	420.4	56.5	518.8	69.7
	10% - <30%		0.17	0.1	0.16	0.1	0.004	0.0	0.02	0.0	0.02	0.3	4.4	2.0	0.18	0.0	4.6	0.6	4.8	0.6
	30% - <50%		0.12	0.1	0.56	0.3	0.005	0.0	0.19	0.1	0.01	0.2	1.5	0.7	0.13	0.0	2.2	0.3	2.4	0.3
	50% - <70%		2.1	1.5	2.3	1.3	0.01	0.0	0.07	0.0	0.17	2.7	9.9	4.4	2.2	0.3	12.3	1.7	14.5	2.0
	70% - <90%		2.5	2.3	3.6	2.1	0.10	0.3	0.93	0.6	0.52	8.4	42.0	18.6	3.1	0.4	46.5	6.3	49.6	6.7
	90% - 100%		33.7	30.8	13.4	7.8	9.8	29.8	15.1	10.1	1.02	16.3	31.6	14.0	44.5	6.0	60.1	8.1	104.6	14.1
	Unknown		25.6	19.0	12.8	6.9	8.8	21.2	1.8	1.2	0	0	0.34	0.2	34.5	4.6	14.9	2.0	49.4	6.6
Topographic Complexity	Very High		0	0	0	0	0	0	0	0	0	0.05	0.0	0	0	0.05	0.0	0.05	0.0	
	High		0.63	0.5	0.38	0.2	0.02	0.0	0.01	0.0	0.03	0.4	1.5	0.7	0.7	0.1	1.9	0.3	2.6	0.3
	Moderate		10.1	7.5	5.1	2.8	0.46	1.1	0.02	0.0	0.86	13.7	28.9	12.8	11.4	1.5	34.0	4.6	45.4	6.1
	Low		26.0	19.3	12.8	6.9	6.1	14.6	13.8	9.1	0.78	12.4	51.5	22.7	32.9	4.4	78.0	10.5	110.9	14.9
	Very Low, Hardbottom		1.7	1.6	1.8	1.1	3.3	10.2	2.5	1.7	0.08	1.3	7.4	3.3	5.2	0.7	11.7	1.6	16.9	2.3
	Very Low, Softbottom		70.9	64.8	151.2	88.3	23.0	69.8	132.7	89.1	4.5	72.3	136.6	60.4	98.4	13.2	420.4	56.5	518.8	69.7
Unknown		25.6	19.0	12.8	6.9	8.8	21.2	1.8	1.2	0	0	0.34	0.2	34.5	4.6	14.9	2.0	49.4	6.6	
Biological Cover	Live Coral		0	0	0.64	0.3	0	0	0.50	0.3	0.01	0.2	0.15	0.1	0.02	0.0	1.3	0.2	1.3	0.2
	Mangrove		1.0	0.7	2.8	1.5	0	0	0	0	0	0	0.58	0.3	1.00	0.1	3.4	0.5	4.4	0.6
	Seagrass		10.7	7.9	97.5	53.0	0	0	10.3	6.8	1.3	20.9	5.0	2.2	12.0	1.6	112.8	15.2	124.8	16.8
	Algae, Hardbottom		38.2	28.3	18.4	10.0	9.9	23.8	15.8	10.5	1.7	27.5	89.1	39.4	49.9	6.7	123.3	16.6	173.2	23.3
	Algae, Softbottom		16.4	15.1	23.8	13.9	14.7	44.6	92.4	62.1	1.9	31.0	102.9	45.6	33.0	4.4	219.1	29.5	252.2	33.9
	No Cover		42.2	38.9	28.1	16.4	8.3	25.2	30.0	20.1	1.3	20.3	27.7	12.3	51.8	7.0	85.8	11.5	137.5	18.5
	Unknown		26.4	19.0	12.9	6.9	8.8	21.2	1.8	1.2	0	0	0.81	0.2	35.2	4.7	15.5	2.1	50.7	6.8
Percent Coral Cover	0% - <10%		33.5	24.8	12.5	6.8	4.0	9.5	1.5	1.0	0.78	12.4	36.0	15.9	38.2	5.1	50.0	6.7	88.3	11.9
	10% - <50%		5.0	3.7	6.9	3.8	6.0	14.3	14.3	9.5	0.95	15.1	53.3	23.5	11.9	1.6	74.5	10.0	86.3	11.6
	50% - <90%		0	0	0.6	0.4	0	0	0.50	0.3	0.01	0.2	0.12	0.1	0.0	0.0	1.2	0.2	1.3	0.2
	Softbottom		70.9	64.8	151.2	88.3	23.0	69.8	132.7	89.1	4.5	72.3	136.6	60.4	98.4	13.2	420.4	56.5	518.8	69.7
	Unknown		25.6	19.0	12.8	6.9	8.8	21.2	1.8	1.2	0	0	0.34	0.2	34.5	4.6	14.9	2.0	49.4	6.6
Dominant Coral Cover	Hard Coral		11.8	8.7	3.7	2.0	0.52	1.2	0.24	0.2	0.32	5.1	40.9	18.0	12.6	1.7	44.8	6.0	57.5	7.7
	Mixed Hard/Soft		9.7	7.2	2.1	1.1	0.13	0.3	0.13	0.1	0.50	8.0	31.6	14.0	10.3	1.4	33.8	4.5	44.2	5.9
	Soft Coral		7.6	5.6	6.9	3.8	9.3	22.2	15.9	10.5	0.86	13.7	16.4	7.2	17.7	2.4	39.2	5.3	56.9	7.6
	No Cover		9.4	8.6	7.3	4.3	0.03	0.1	0.02	0.0	0.06	1.0	0.56	0.2	9.5	1.3	7.9	1.1	17.3	2.3
	Softbottom		70.9	64.8	151.2	88.3	23.0	69.8	132.7	89.1	4.5	72.3	136.6	60.4	98.4	13.2	420.4	56.5	518.8	69.7
	Unknown		25.6	19.0	12.8	6.9	8.8	21.2	1.8	1.2	0	0	0.34	0.2	34.5	4.6	14.9	2.0	49.4	6.6
	Back Reef		0.3	0.2	0.4	0.2	0	0	0.5	0.3	0	0	0.4	0.2	0.3	0.1	1.2	0.2	1.5	0.2
Geographic Zone	Bank/Shelf		85.2	64.1	159.4	84.9	23.3	56.7	141.5	95.4	5.2	83.0	190.8	86.7	113.7	63.1	491.8	88.4	605	82.2
	Channel		0.1	0.1	0.3	0.2	0	0	0	0	0.02	0.4	0.2	0.1	0.2	0.1	0.5	0.1	0.7	0.1
	Dredged		0	0	4.4	2.4	0	0	0	0	0	0	0	0	0.0	0.0	4.4	0.8	4.4	0.6
	Fore Reef		5.5	4.1	8.3	4.4	0	0	4.5	3.0	0.6	9.8	6.1	2.8	6.1	3.4	18.9	3.4	25.0	3.4
	Lagoon		1.9	1.4	0.7	0.4	0	0	0	0	0.0	0.5	4.6	2.1	1.9	1.0	5.3	1.0	7.2	1.0
	Reef Crest		1.2	0.9	0.9	0.5	0	0	0.4	0.3	0.1	2.3	1.0	0.4	1.4	0.8	2.3	0.4	3.7	0.5
	Reef Flat		1.5	1.1	2.0	1.1	0	0	0.3	0.2	0.2	2.5	1.7	0.8	1.6	0.9	4.0	0.7	5.6	0.8
	Reef Ridge Complex		35.6	26.7	2.0	1.1	17.7	43.2	1.1	0.7	0	0	13.6	6.2	53.3	29.6	16.7	3.0	70.0	9.5
	Salt Pond		0.1	0.1	1.8	1.0	0	0	0	0	0	0	0.4	0.2	0.1	0.1	2.3	0.4	2.4	0.3
	Shoreline Intertidal		1.7	1.3	7.6	4.0	0.01	0.03	0											

Appendix A.1. cont. Habitat Classes By Region

Coral cover - Hardbottom areas only		NEPR Inside Reserve		NEPR Outside Reserve		Offshore Inside Reserve		Offshore Outside Reserve		Culebra Inside Reserve		Culebra Outside Reserve		All Areas Inside Reserve		All Areas Outside Reserve		All Areas Summary	
		km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%
Total mapped hardbottom		38.5	65.8	20.0	34.2	9.9	37.9	16.3	62.1	1.7	1.9	89.4	98.1	50.1	28.5	125.7	71.5	175.9	100
Percent Coral Cover	0% - <10%	33.5	87.1	12.5	62.4	4.0	40.0	1.5	9.4	0.78	44.7	36.0	40.3	38.2	76.3	50.0	39.8	88.3	50.2
	10% - <50%	5.0	12.9	6.9	34.5	6.0	60.0	14.3	87.6	0.95	54.5	53.3	59.6	11.9	23.7	74.5	59.2	86.3	49.1
	50% - <90%	0	0.0	0.6	3.1	0	0.0	0.50	3.0	0.01	0.8	0.12	0.1	0.0	0.0	1.2	1.0	1.3	0.7
Dominant Coral Cover	Hard Coral	11.8	30.7	3.7	18.6	0.52	5.2	0.24	1.5	0.32	18.3	40.9	45.7	12.6	25.2	44.8	35.6	57.5	32.7
	Mixed Hard/Soft	9.7	25.3	2.1	10.3	0.13	1.3	0.13	0.8	0.50	28.7	31.6	35.4	10.3	20.6	33.8	26.9	44.2	25.1
	Soft Coral	7.6	19.7	6.9	34.6	9.3	93.2	15.9	97.6	0.86	49.3	16.4	18.3	17.7	35.3	39.2	31.2	56.9	32.4
	No Cover	9.4	24.3	7.3	36.5	0.03	0.3	0.02	0.1	0.06	3.7	0.56	0.6	9.5	18.9	7.9	6.3	17.3	9.9

Appendix A.2. Combined Habitat Classes By Region

		NEPR Inside Reserve		NEPR Outside Reserve		Offshore Inside Reserve		Offshore Outside Reserve		Culebra Inside Reserve		Culebra Outside Reserve		All Areas Inside Reserve		All Areas Outside Reserve		All Areas Summary	
Classification Attribute		km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%
Total Area, Proportion by Region		135.1	42.3	184.1	57.7	41.7	21.7	150.7	78.3	6.3	2.7	226.4	97.3	183.1	24.6	561.2	75.4	744.3	100.0
<i>Dominant Coral</i>	<i>Percent Coral</i>	NEPR NER		NEPR		O. NER		Offshore		C. NER		Culebra		All NER		All Outside		Summary	
Live Coral	Hard Coral 50% - <90%	0	0	0	0	0	0	0	0	0.001	0.02	0.1	0.05	0.001	0.0	0.1	0.02	0.1	0.02
	Hard Coral 10% - <50%	0.19	0.1	0.1	0.1	0.0	0.00	0.0	0.0	0	0	30	13	0.2	0.1	29.8	5.3	30.0	4.03
	Hard Coral 0% - <10%	11.6	8.6	3.6	2.0	0.5	1.2	0.2	0.2	0.3	4.9	11.0	4.88	12.4	6.8	14.9	2.7	27.3	3.67
	Mixed Hard/Soft 50% - <90%	0.0	0	0.102	0	0	0	0.0	0.00	0	0	0.002	0.0	0.003	0	0.1	0.02	0.1	0.01
	Mixed Hard/Soft 10% - <50%	0.9	1	1.2	0.7	0.1	0.2	0.0	0.0	0.3	4.20	16.9	7.45	1.2	0.7	18.1	3.2	19.3	2.6
	Mixed Hard/Soft 0% - <10%	9.0	7	0.8	0.4	0.1	0.1	0.1	0.1	0.2	3.71	14.8	6.52	9.2	5.0	15.6	2.8	24.9	3.3
	Soft Coral 50% - <90%	0.0	0.0	0.53	0.29	0.0	0	0.5	0.33	0	0	0.01	0.004	0.01	0.01	1.0	0.18	1.0	0.14
	Soft Coral 10% - <50%	3.9	2.9	5.6	3.0	5.9	14.1	14.2	9.4	0.7	10.8	6.7	3.0	10.4	5.7	26.5	4.7	37.0	5.0
	Soft Coral 0% - <10%	3.7	3	0.8	0.4	3.4	8.1	1.2	0.8	0.2	2.8	9.7	4.3	7.3	4.0	11.6	0.5	18.9	2.5
	No Cover 0% - <1%	9.4	7	7.3	4.0	0.0	0.1	0.0	0.0	0	1	1	0.2	9.5	5.2	7.9	3.0	17.3	2.3
Softbottom	70.9	52.5	151.3	82.2	23.0	55.0	132.7	88.0	4.5	72.3	136.6	60.3	98.4	53.7	420.5	74.9	518.9	69.7	
Unknown	26	19	12.8	7	8.8	21	1.8	1	0.0	0	0.3	0	34.5	19	14.9	3	49.4	7	
<i>Biological Cover</i>	<i>Percent Cover</i>	NEPR NER		NEPR		O. NER		Offshore		C. NER		Culebra		All NER		All Outside		Summary	
Live Coral	Patchy (50% - <90%)	0.00	0.00	0.6	0.34	0.0	0.00	0.5	0.33	0	0.01	0.1	0.05	0.00	0.00	1.2	0.22	1.2	0.17
Live Coral	Patchy (10% - <50%)	0.00	0.00	0.0	0.00	0.000	0.00	0.001	0.00	0	0.22	0.039	0.02	0.02	0.01	0.05	0.01	0.1	0.01
Algae, Hardbottom	Continuous (90% - 100%)	29.2	21.58	7.1	3.84	3.9	9.44	1.1	0.70	0.5	8.63	18.1	8.01	33.6	18.37	26.3	4.68	59.9	8.05
Algae, Hardbottom	Patchy (50% - <90%)	8.9	6.59	11.3	6.13	6.0	14.35	14.7	9.75	1.2	18.54	65.8	29.08	16.1	8.77	91.8	16.36	107.8	14.50
Algae, Hardbottom	Patchy (10% - <50%)	0.17	0.13	0.1	0.04	0.0	0.00	0.0	0.02	0.022	0.35	5.15	2.28	0.2	0.11	5.3	0.94	5.5	0.73
Algae, Softbottom	Continuous (90% - 100%)	0.7	0.52	0.0	0.00	8.2	19.59	25.1	16.65	0.1	1.26	29.6	13.07	9.0	4.89	54.7	9.75	63.7	8.56
Algae, Softbottom	Patchy (50% - <90%)	2.2	1.63	20.2	10.98	1.8	4.35	5.4	3.60	1.8	28.13	33.4	14.76	5.8	3.15	59.1	10.52	64.8	8.71
Algae, Softbottom	Patchy (10% - <50%)	13.5	10.00	0.9	0.51	4.7	11.25	61.9	41.07	0.1	1.60	39.9	17.64	18.3	10.00	102.8	18.32	121.1	16.28
Seagrass	Continuous (90% - 100%)	6.1	4.54	28.7	15.59	0	0	2.7	1.81	1	16.76	2.6	1.16	7.2	3.92	34.0	6.06	41.2	5.54
Seagrass	Patchy (50% - <90%)	3.5	2.61	4.7	2.57	0	0	2.3	1.51	0	0.85	0.9	0.38	1.3	0.69	82.4	14.69	83.7	11.25
Seagrass	Patchy (10% - <50%)	1.1	0.78	75.6	41.09	0	0	5.3	3.50	0	3.31	1.5	0.68	3.6	1.96	7.9	1.40	11.5	1.54
Mangrove	Continuous (90% - 100%)	1	0.74	2.6	1.41	0	0	0	0	0	0	1	0.25	1.0	0.54	3.2	0.57	4.2	0.56
Mangrove	Patchy (50% - <90%)	0	0	0.323	0.18	0	0	0	0	0	0	0	0	0	0	0.3	0.06	0.3	0.04
Mangrove	Patchy (10% - <50%)	0	0	1.759	0.96	0	0	0	0	0	0	0	0	0	0	1.8	0.31	1.8	0.24
No Cover	Continuous (90% - 100%)	42.2	31.24	0.7	0.39	8.3	19.83	30.0	19.88	1.3	20.35	27.7	12.26	51.8	28.27	58.4	10.41	110.2	14.81
Unknown	26	19.54	29.4	15.97	8.8	21.18	1.8	1.18	0.0	0.00	0.8	0.36	35.2	19.25	32.0	5.70	67.2	9.04	
<i>Habitat Overview</i>	<i>Modifier</i>	NEPR NER		NEPR		O. NER		Offshore		C. NER		Culebra		All NER		All Outside		Summary	
Habitat Overview	Coral Reef (High Relief, High Coral)	0.66	0.49	1.48	0.81	0.01	0.02	0.01	0.01	0.42	6.74	19.92	8.80	1.1	0.60	21.4	3.82	22.5	3.02
	Coral Reef (High Relief, Low Coral)	10.03	7.42	3.96	2.15	0.47	1.12	0.02	0.01	0.46	7.33	10.60	4.68	11.0	5.98	14.6	2.60	25.5	3.43
	Coral Reef (Low Relief, High Coral)	4.31	3.19	6.05	3.29	5.95	14.25	14.75	9.78	0.54	8.59	33.49	14.79	10.8	5.89	54.3	9.67	65.1	8.75
	Coral Reef (Low Relief, Low Coral)	23.47	17.37	8.53	4.63	3.51	8.41	1.50	1.00	0.3	5	25	11	27.3	14.90	35.5	6.32	62.8	8.43
	Seagrass (Continuous)	6.06	4.48	75.59	41.07	0.01	0.04	2.72	1.81	1.05	17	2.52	1.11	7.1	3.89	80.8	14.40	88.0	11.82
	Seagrass (Patchy)	4.43	3.28	20.94	11.38	0.00	0.00	7.54	5.00	0.3	4	2.34	1.03	4.7	2.56	30.8	5.49	35.5	4.77
	Algae, Softbottom (Continuous)	0.70	0.52	0.94	0.51	8.16	19.55	25.11	16.65	0.08	1.26	29.60	13.07	8.9	4.88	55.6	9.92	64.6	8.68
	Algae, Softbottom (Patchy)	15.71	11.63	22.82	12.40	6.51	15.60	67.34	44.67	1.86	29.73	73.33	32.40	24.1	13.15	163.5	29.13	187.6	25.21
	Mangrove (Continuous)	1	1	1.76	0.96	0	0	0	0	0	0	1	0	1.0	0.54	2.3	0.42	3.3	0.45
	Mangrove (Patchy)	0	0	1.04	1	0	0	0	0	0	0	0	0	0.0	0	1.0	0.19	1.0	0.14
	Sand (No Cover)	42.21	31.24	25.08	13.62	8.27	19.82	29.96	19.88	1.27	20.35	23.11	10.21	51.8	28.26	78.1	13.93	129.9	17.46
	Mud (No Cover)	1	1	2.99	1.62	0	0	0.00	0	0	0	1	1	0.8	0.42	4.5	0.79	5.2	0.70
	Artificial	0.001	0.001	0.11	0.06	0	0	0.00	0	0	0	0.01	0	0	0	0.1	0.02	0.1	0.02
	Unknown	26	19	12.77	6.94	8.84	21.18	1.78	1.18	0	0	0.34	0.15	34.5	18.83	14.9	2.65	49.4	6.64

SHALLOW-WATER BENTHIC HABITATS OF NORTHEAST PUERTO RICO AND CULEBRA ISLAND
NOAA Technical Memorandum NOS NCCOS 200



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