CHAPTER 2: BENTHIC HABITATS OF VIEQUES, PUERTO RICO

Laurie J. Bauer[1,2,], Matthew S. Kendall[1], Adam G. Zitello[1,2], and Tim Battista[1]*

[1]Center for Coastal Monitoring and Assessment, National Centers for Coastal Ocean Science, National Ocean Service, NOAA, 1305 East-West Hwy, Silver Spring, MD 20910

[2]Consolidated Safety Services, Inc., Fairfax, VA 22030, under NOAA Contract No. DG133C07NC0616

[*]Corresponding author: laurie.bauer@noaa.gov

2.1 INTRODUCTION

This chapter describes the creation and assessment of benthic habitat maps for the nearshore waters of Vieques. The objective was to provide spatially-explicit information on the habitat types, biological cover and live coral cover of Vieques' coral reef ecosystem. These fine-scale habitat maps, generated by interpretation of 2006-2008 IKONOS imagery and orthophotography, represent a significant improvement from NOAA's previous digital maps of the U.S. Caribbean (Kendall et al. 2001) due to an expanded habitat classification scheme, smaller minimum mapping unit (MMU), and more recent imagery. The previous map NOAA map of Vieques was created using 1999 imagery with an MMU of one acre (~4047 m^2), while the new map was created with imagery collected in 2006-2008 with an MMU of 1000 m^2. A discussion of previous mapping efforts in Vieques can be found in Bauer et al. (2008).

The chapter consists of four primary components: 1) a description of the benthic habitat classification scheme used to classify habitats, 2) a discussion of the techniques used for map creation, 3) an assessment of the map accuracy, and 4) a summary of map statistics, habitat distributions, and deliverables. The maps will be used by managers and scientists for planning, research and monitoring activities, and will support the management and conservation of the marine waters of Vieques. The Vieques benthic habitat map and a suite of associated products are available to the public on a NOAA Biogeography Branch website devoted to this mapping effort (http://ccma.nos.noaa.gov/ecosystems/coralreef/vieques.html).

2.2 BENTHIC HABITAT CLASSIFICATION SCHEME

The Vieques habitat classification scheme defines benthic habitats based on five attributes: 1) broad geographic zone, 2) geomorphological structure type, 3) dominant biological cover, 4) degree of live coral cover,

Geographic Zone	Geomorphological Structure	Biological Cover	Percent Hardbottom
Land	Coral Reef and Hardbottom	**Major Cover**	0% - <10%
Salt Pond	Rock/Boulder	Algae	10% - <30%
Shoreline Intertidal	Aggregate Reef	Seagrass	30% - <50%
Lagoon	Individual Patch Reef	Live Coral	50% - <70%
Reef Flat	Aggregated Patch Reefs	Mangrove	70% - <90%
Back Reef	Spur and Groove	Coralline Algae	90% - 100%
Reef Crest	Pavement	No Cover	Unknown
Fore Reef	Pavement with Sand Channels	Unknown	
Bask/Shelf	Reef Rubble	**Percent Major Cover**	
Bank/Shelf-Escarpment	Rhodoliths	10% - <50%	
Channel	Unknown	50% - <90%	
Dredged	Unconsolidated Sediment	90% - 100%	
Unknown	Sand	Unknown	
	Mud	**Percent Coral Cover**	
	Sand with Scattered Coral and Rock	0% - <10%	
	Unknown	10% - <50%	
	Other Delineations	50% - <90%	
	Land	90% - 100%	
	Artificial	Unknown	
	Unknown		

Figure 2.1. The classification scheme defines benthic habitats with five primary attributes (described by separate boxes) and several hierarchical levels of classification therein.

and 5) percent hardbottom. A hierarchical structure of describing features at varying levels of detail was used so that numerous detailed habitats are encompassed by more broadly defined habitat classes. This hierarchy provides users with the ability to expand and collapse the detail of the habitat map to suit their needs. Every feature in the benthic habitat map is assigned a designation from each level of the scheme (Figure 2.1). The ability to apply any component of this scheme is dependent on being able to identify and delineate a given feature in remotely sensed imagery.

Many factors were considered in the development of this habitat classification scheme including: requests of the management community, existing classification schemes for coastal ecosystems, quantitative *in situ* habitat data, minimum mapping unit (MMU) and spectral limitations of remotely sensed imagery (Kendall et al. 2001). The habitat classification scheme used in Vieques was based on the evolution of schemes developed by NOAA in efforts to map the U.S. Caribbean and Pacific Islands (Kendall et al. 2001; Battista et al. 2007a,b). A very similar version of the scheme used here was also used in the recent mapping of St. John, USVI (Zitello et al. 2009), with the exception of an additional modifier for the Vieques map (i.e., percent hardbottom).

The primary difference between the new scheme and the one used by Kendall et al. (2001) in the previous mapping of Vieques is the separation of biological cover from habitat structure and additional detailed classes. Dominant biological cover, live coral cover, and percent hardbottom were not identified in the previously used scheme.

The new scheme is also improved in other ways as compared to the previous NOAA schemes used for benthic habitat mapping in the Pacific (e.g., Battista et al. 2007a,b). The primary difference was the deviation from coral-centric classification rules to a biological dominance scheme in which benthic habitats were classified based on the dominant biological cover type present on each feature. In previous NOAA coral reef habitat schemes, the biological cover component was assigned in a step-wise progression to first capture the presence of live coral and then attempt to classify any other biological cover if coral was not present. In other words, during map creation the interpreter would assign a polygon to the "Live Coral" biological cover class if there was 10% or greater live coral cover even if the polygon was predominantly covered by another biological cover type. For example, a patch reef covered by 15% live coral and 85% turf algae would be described in the previous classification schemes as "Live Coral 10% - <50%". This approach often mislead map users in over-stating the degree of live coral cover at the expense of the more prevalent biological cover type.

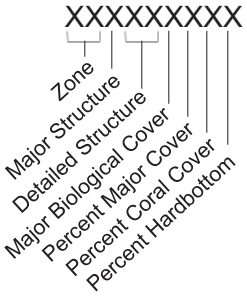


Figure 2.2. Schematic of each attribute's position in the UniqueID code of the classification scheme.

In NOAA's new Vieques habitat classification scheme, biological cover was described simply as the dominant cover type on each feature of the map. Percent cover of live coral was mapped separately in the Vieques scheme by the introduction of a new map attribute *Percent Coral Cover*. This attribute describes the percent live coral cover (includes "hard" scleractinians and "soft" gorgonians) for every feature. It is important to note that Percent Coral Cover refers only to the hardbottom component of any mapped polygon. For instance, an area of sand with some small scattered patch reefs in it could be classified as 10% - <50% live coral cover even though 90% of the polygon is bare sand.

Every unique combination of classification attributes was provided a distinct identifier in the *UniqueID* field of the GIS layer. *UniqueID* consists of an 8-digit number string with each position in the string corresponding to a specific map attribute (Figure 2.2). Within each attribute, different classifications were assigned discrete numbers.

Geographic Zones

Thirteen mutually exclusive zones can be identified from land to open water corresponding to typical insular shelf and coral reef geomorphology. These zones include: *Land, Salt Pond, Shoreline Intertidal, Reef Flat, Lagoon, Back Reef, Reef Crest, Fore Reef, Bank/Shelf, Bank/Shelf Escarpment, Channel, Dredged, and Unknown*. Figures 2.3 – 2.5 illustrate zone types across typical cross-sections of the island shelf when the reef feature is either separated from shore by a lagoon (Figure 2.3), fringing the shore (Figure 2.4), or not emergent (Figure 2.5). Zone refers only to each benthic community's location and does not address substrate or biological cover types that are found within. For example, the *Lagoon* zone may include patch reefs and reef rubble; however, these are considered structural elements that may or may not occur within the lagoon zone and therefore, are not used to define it (Kendall et al. 2001). A brief description of each zone is provided in the following text.

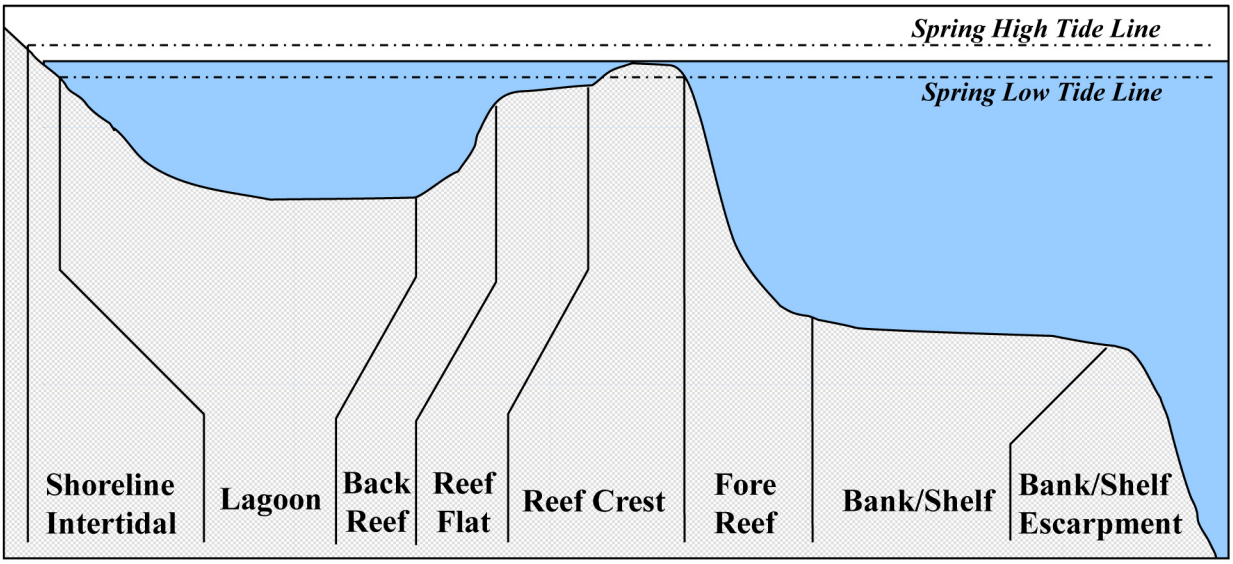


Figure 2.3. Cross-section of zone types where a barrier reef is present. Reef is separated from the shore by a relatively wide, deep lagoon.

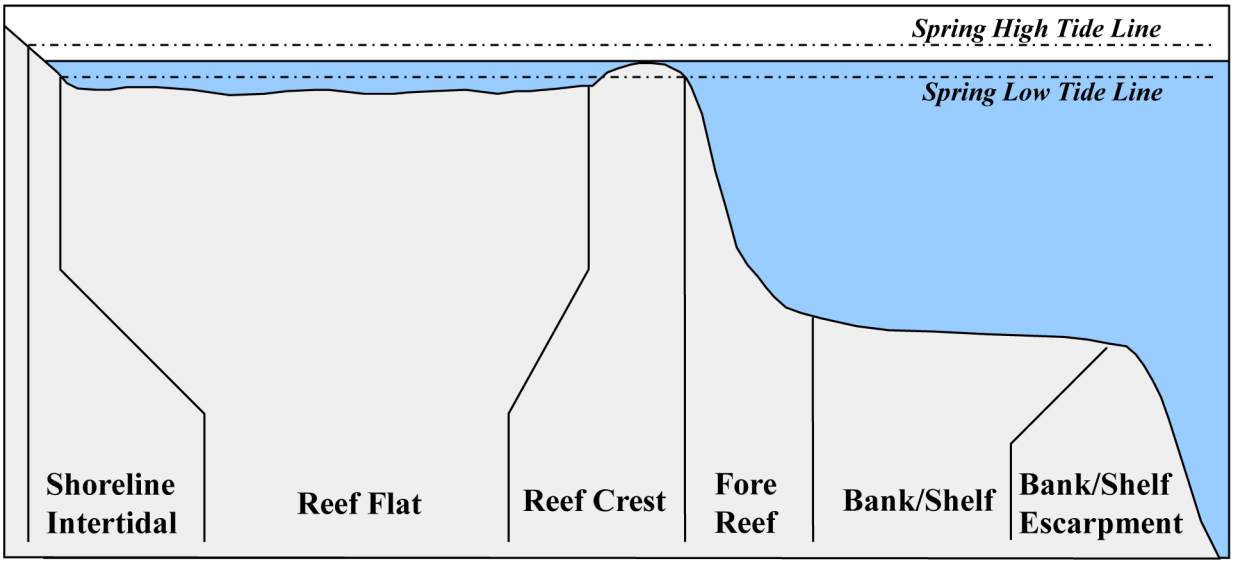


Figure 2.4. Cross-section of zone types where a fringing reef is present. Reef platform is continuous with the shore.

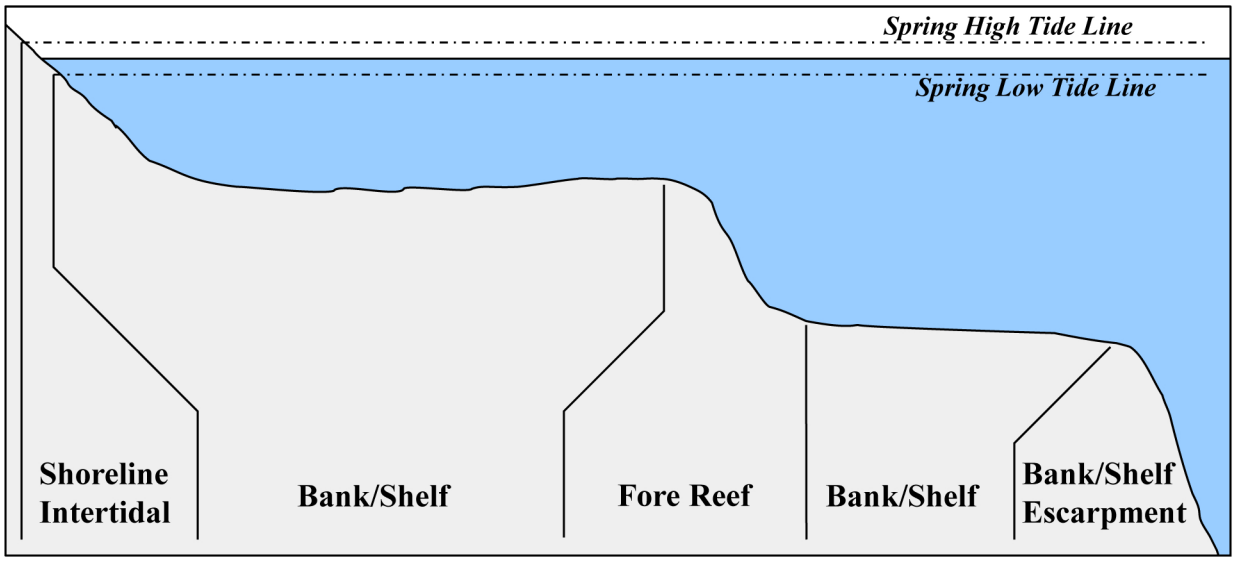


Figure 2.5. Cross-section of zone types where no emergent reef crest is present.

Land

Terrestrial features at or near 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). (Unique ID = 10)

Figure 2.6. Depiction of shoreline delineations on unconsolidated (left) and rocky (right) coastlines. A red line highlights each shoreline on satellite imagery.

Salt Pond

Enclosed area just landward of the shoreline with a permanent or intermittent flooding regime of saline to hypersaline waters (Figure 2.7). When a mangrove fringe lined the inland water body, this was also included in the *Salt Pond* zone (as opposed to *Shoreline Intertidal* as described below). (Unique ID = 11)

Figure 2.7. Depictions of the *Salt Pond* zone just inshore of Purple Beach (left). A red polygon outlines the feature on satellite imagery. In Vieques, these features are typically lined by mangroves (right).

Shoreline Intertidal

Area between the spring high tide line (or landward edge of emergent vegetation when present) and lowest spring tide level. Emergent segments of barrier reefs are excluded from this zone and instead are defined below as *Reef Crest*. Typically, this zone is narrow due to the small tidal range in Puerto Rico (Figure 2.8). While present island-wide, the feature is often too narrow to be mapped on steep shorelines due to the scale of the imagery and the MMU. (Unique ID = 12)

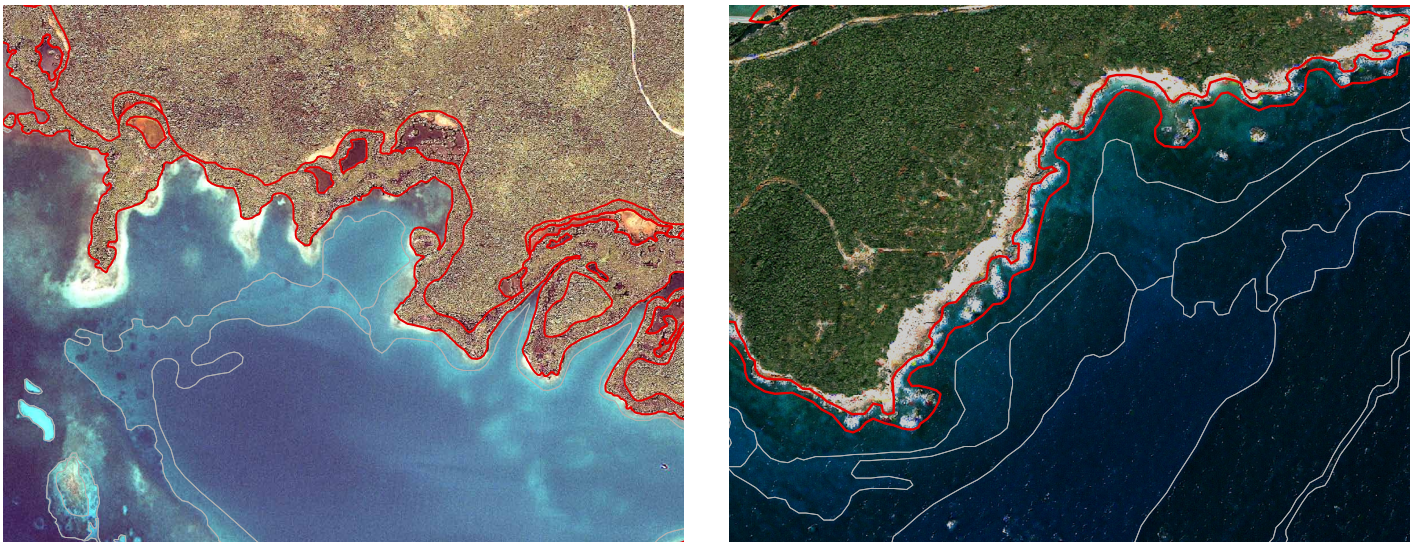


Figure 2.8. Representation of two different types of *Shoreline Intertidal* zones. A low energy mangrove shoreline (left) and a high energy rocky shoreline (right) on the east end of Vieques.

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 *Bank/Shelf* and *Reef Crest* zones (Figure 2.9). (Unique ID = 13)

Reef Flat

Shallow, semi-exposed area of little relief between the *Shoreline Intertidal* zone and the *Reef Crest* of a fringing reef. This broad, flat area often exists just landward of a *Reef Crest* and may extend to the shoreline or drop into a *Lagoon*. This zone is often somewhat protected from the high-energy waves commonly experienced on the *Bank/Shelf* and *Reef Crest* zones (Figure 2.10). (Unique ID = 14)

Figure 2.9. View of the *Lagoon* zone on satellite imagery at Playa Blanca. A red polygon outlines the feature.

Figure 2.10. Depictions of the *Reef Flat* zone on satellite imagery in Ensenada Honda. A red polygon outlines the feature.

Back Reef
Area just 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. (Unique ID = 15)

Reef Crest
The flattened, emergent (especially during low tides) or nearly emergent segment of a reef. This high wave energy zone 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 2.11). (Unique ID = 16)

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 (2.11). 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 2.4). (Unique ID = 17)

Bank/Shelf
Deeper water area (relative to the shallow water in a lagoon) extending offshore from the seaward edge of the *Fore Reef* or shoreline to the beginning of the escarpment where the insular shelf drops off into deep, oceanic water (Figure 2.11). 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. (Unique ID = 18)

Figure 2.11. A series of satellite images illustrating the transition from *Reef Crest* (left) to *Fore Reef* (middle) to *Bank/Shelf* (right) zones seaward of Puerto Negro. Each zone is depicted in color on the respective map.

Bank/Shelf Escarpment (19)
This zone begins on the oceanic edge of the *Bank/Shelf*, where depth increases rapidly into deep, oceanic water and exceeds the depth limit of features visible in optical imagery around Vieques. This zone is intended to capture the transition from the shelf to deep waters of the open ocean.

Channel (20)
Naturally occurring channels that often cut across several other zones.

Dredged (21)
Area in which natural geomorphology is disrupted or altered by excavation or dredging.

Unknown (99)
Zone indistinguishable due to turbidity, cloud cover, water depth, or other interference with an optical signature of the seafloor.

Geomorphological Structure Types

Fifteen distinct and non-overlapping geomorphologic structure types were described that can be mapped by visual interpretation of remotely-sensed imagery. Habitats or features that cover areas smaller than the MMU were not considered. For example, sand halos surrounding patch reefs are often too small to be mapped independently. Structure refers only to predominate physical composition of the feature and does not address location (e.g., on the shelf or in the lagoon). The structure types are defined in a collapsible hierarchy ranging

from four major classes (*Coral Reef and Hardbottom*, *Unconsolidated Sediment*, *Other Delineations*, and *Unknown*), to fifteen detailed classes (*Rock/Boulder, Spur and Groove, Individual Patch Reef, Aggregated Patch Reefs, Aggregate Reef, Reef Rubble, Pavement, Pavement with Sand Channels, Rhodoliths, Sand, Mud, Sand with Scattered Coral and Rock, Artificial, Land*, and *Unknown*).

Coral Reef and Hardbottom

Areas of both shallow and deep-water seafloor with solid substrates including bedrock, boulders and deposition of calcium carbonate by reef building organisms. Substrates typically lack a thick sediment cover, but a thin veneer of sediment may be present at times. Detailed structure classes within this category include *Rock/Boulder, Spur and Groove, Individual Patch Reef, Aggregated Patch Reefs, Aggregate Reef, Reef Rubble, Pavement, Pavement with Sand Channels*, and *Rhodoliths*. (Unique ID = 1)

Rock/Boulder

A primarily continuous exposure of solid carbonate blocks or volcanic rock extending offshore from the island bedrock or aggregation of loose carbonate or volcanic rock fragments that have been detached and transported from their native beds (Figure 2.12). Individual boulders range in diameter from 0.25 – 3 m as defined by the Wentworth scale (Wentworth 1922). (Unique ID = 33)

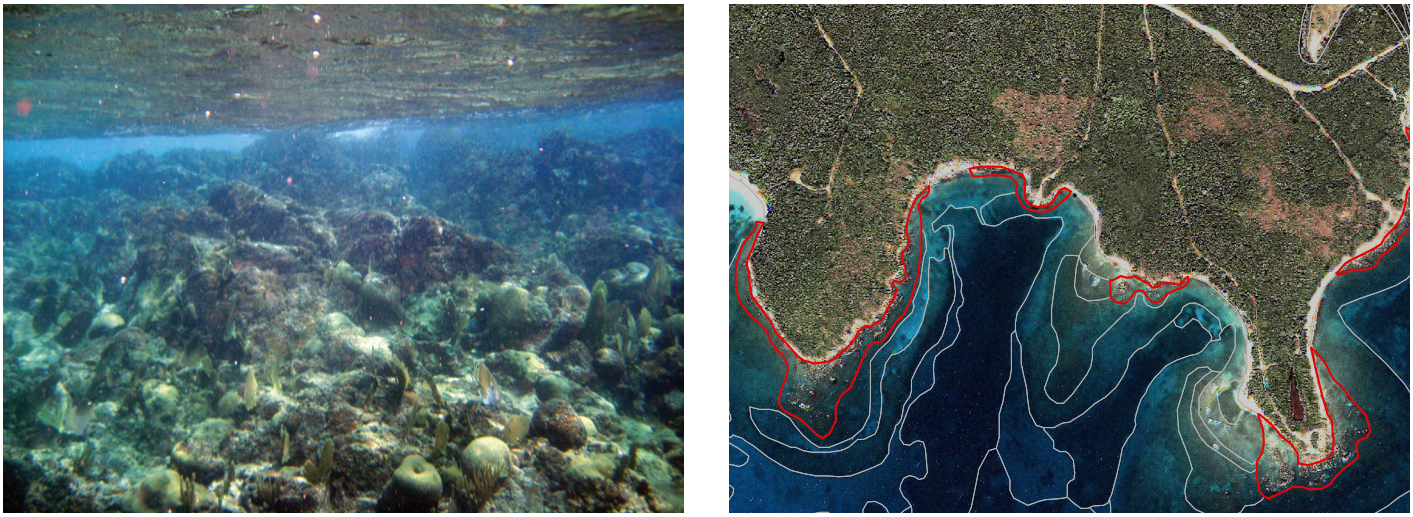


Figure 2.12. Depictions of *Rock/Boulder* structure in Vieques. A red polygon outlines the feature on satellite imagery.

Aggregate Reef

Continuous, high-relief coral formation of variable shapes lacking sand channels of *Spur and Groove*. Includes linear coral formations that are oriented parallel to shore or the shelf edge (Figure 2.13). This class is used for such commonly referred to terms as linear reef, fore reef or fringing reef. (Unique ID = 10)

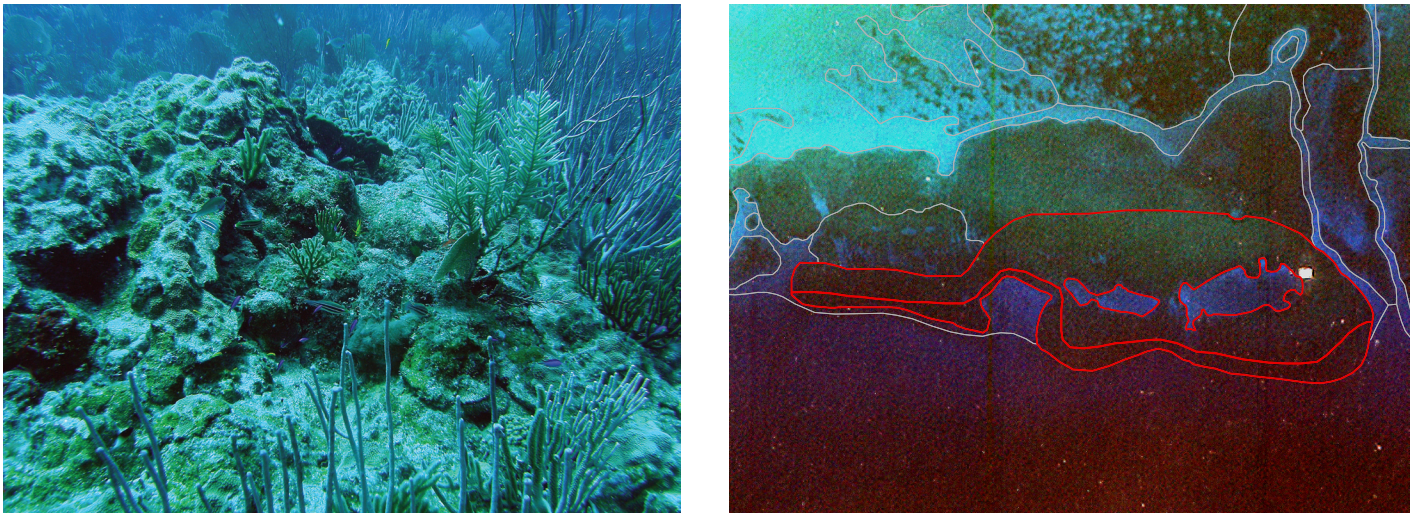


Figure 2.13. Depictions of *Aggregate Reef* structure in Vieques. A red polygon outlines the feature on satellite imagery.

Individual Patch Reef

Patch reefs are 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 shore 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 2.14). *Individual Patch Reefs* are larger than or equal to the MMU. (Unique ID = 11)

Aggregated Patch Reefs

Having the same defining characteristics as an *Individual Patch Reef.* This class refers to clustered patch reefs that individually are too small (less than the MMU) or are too close together to map separately. Where aggregated patch reefs share sand halos, the halo is included in the polygon (Figure 2.14). (Unique ID = 12)

Figure 2.14. Comparison of patch reef delineations west of Isabel Segunda. Due to the influence of minimum mapping units, patch reefs of the same complex are designated by either *Individual Patch Reef* (left) or *Aggregated Patch Reefs* (right). Red polygons outline the features on satellite imagery.

Spur and Groove

Structure having alternating sand and coral formations that are oriented perpendicular to the shore or reef crest. The coral formations (spurs) of this feature typically have a high vertical relief relative to pavement with sand channels (Figure 2.15) and are separated from each other by 1-5 meters of sand or hard-bottom (grooves), although the height and width of these elements may vary considerably (Figure 2.15). This habitat type typically occurs in the *Fore Reef* or *Bank/Shelf Escarpment* zone. (Unique ID = 13)

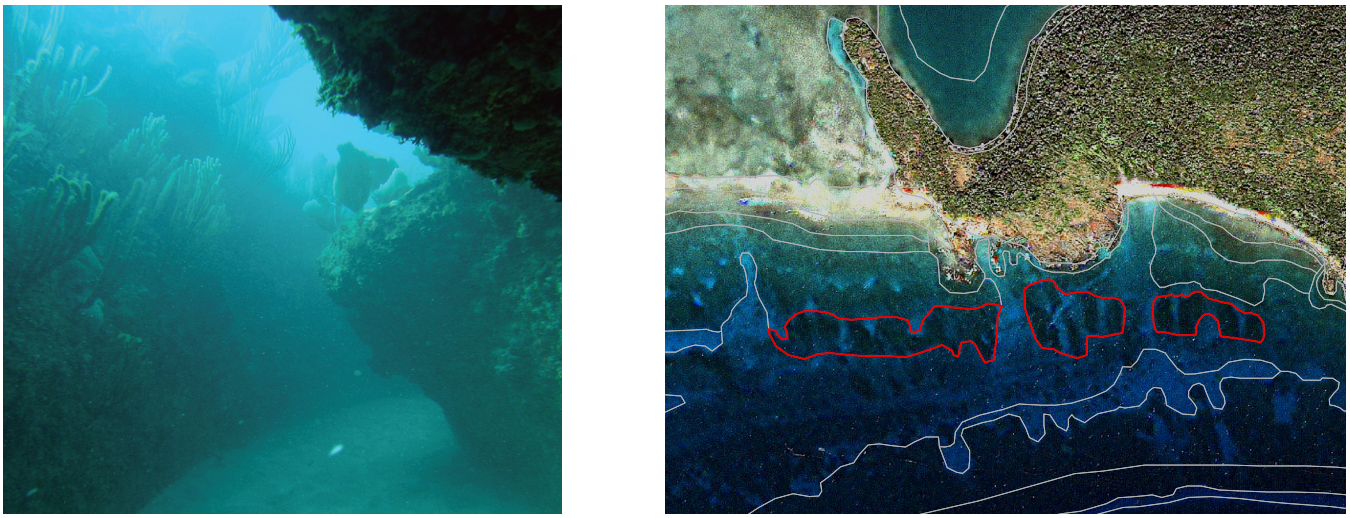


Figure 2.15. Depictions of *Spur and Groove* structure in Vieques. A red polygon outlines the features on satellite imagery, south of Punta Carenero.

Pavement

Flat, low-relief, solid carbonate rock in regularly broad areas with coverage of algae, hard coral, gorgonians, zooanthids or other sessile vertebrates that are dense enough to partially obscure the underlying surface (Figure 2.16). On less colonized *Pavement* features, rock may be covered by a thin sand veneer or turf algae. (Unique ID = 14)

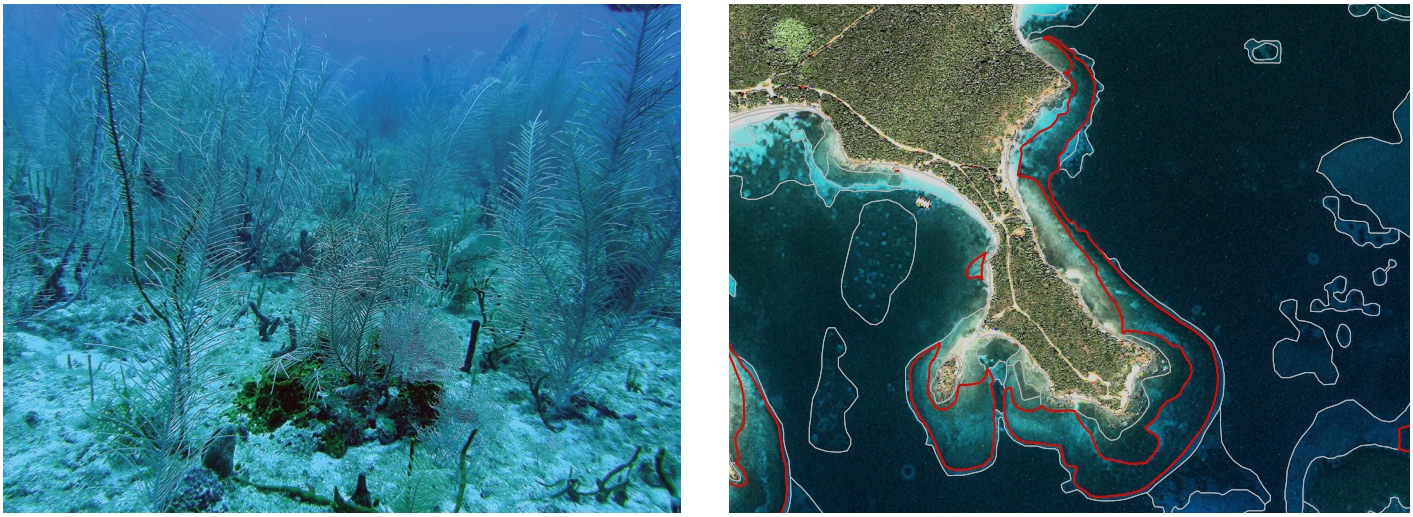


Figure 2.16. Depictions of *Pavement* structure in Vieques. A red polygon outlines the features on satellite imagery.

Pavement with Sand Channels

Habitats of pavement with alternating sand/surge channel formations that are oriented perpendicular to the shore or *Bank/Shelf Escarpment*. The sand/surge channels of this feature have low vertical relief relative to *Spur and Groove* formations. This habitat type occurs in areas exposed to moderate wave surge such as the *Bank/Shelf* zone (Figure 2.17). (Unique ID = 15)

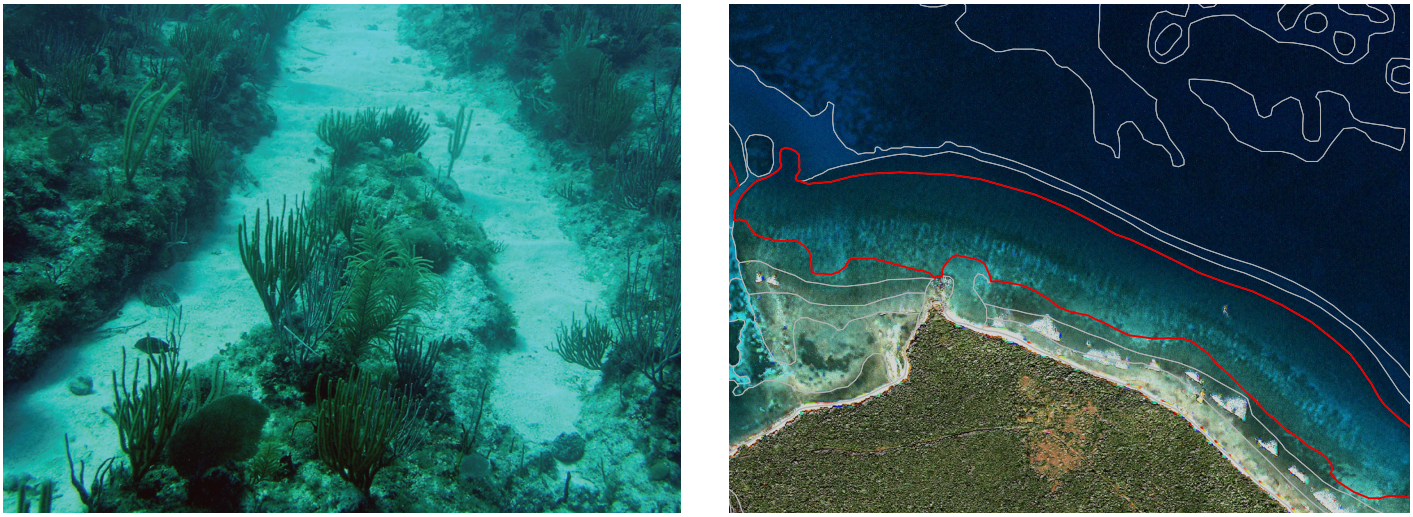


Figure 2.17. Depictions of *Pavement with Sand Channels* structure in Vieques. A red polygon outlines the features on satellite imagery.

Reef Rubble

Dead, unstable coral rubble often colonized with turf, filamentous or other macroalgae. 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 2.18). (Unique ID = 16)

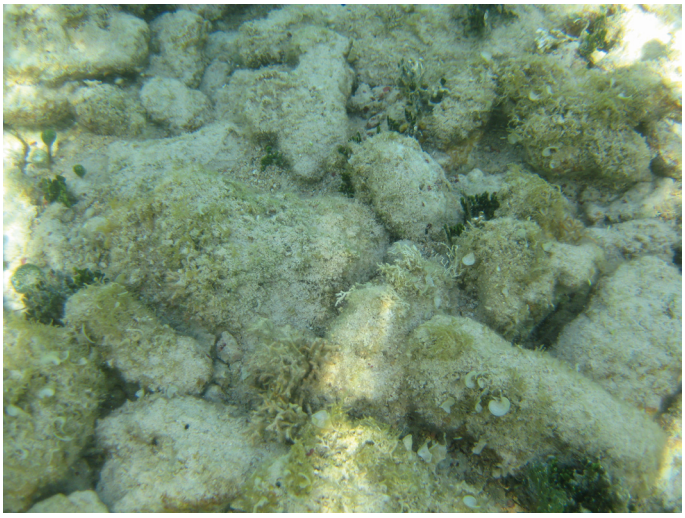


Figure 2.18. Depictions of *Reef Rubble* structure in Vieques. A red polygon outlines the features on satellite imagery.

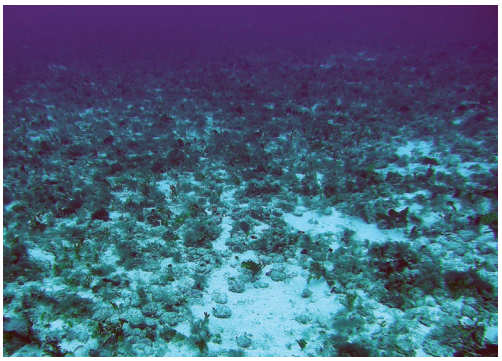


Figure 2.19. Typical *Rhodolith* bed north of Vieques.

Rhodoliths

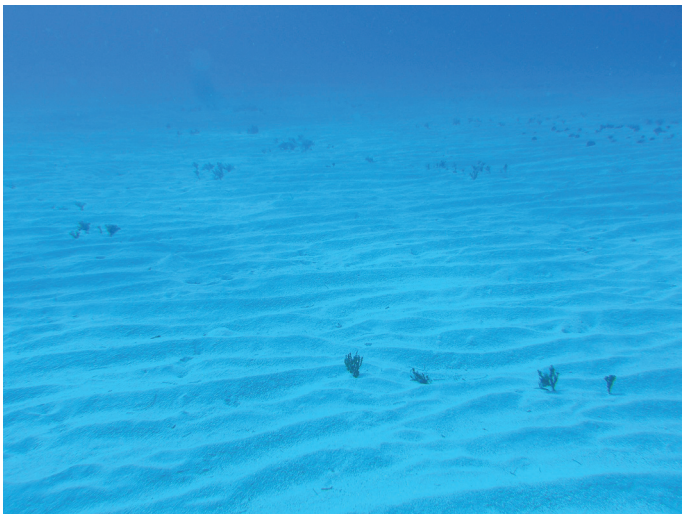
Aggregation of cylindrical, discoidal, or irregular shaped calcareous nodules averaging approximately 6 cm in diameter. These unattached fragments are colonized by successive layers of coralline red algae. Commonly found in offshore topographic depressions (Figure 2.19). (Unique ID = 17)

Unconsolidated Sediment

Areas of the seafloor consisting of small particles (<.25 m) with less than 10% cover of large stable substrate. Detailed structure classes of softbottom include *Sand*, *Mud*, and *Sand with Scattered Coral and Rock*. (Unique ID = 2)

Sand

Coarse sediment typically found in areas exposed to currents or wave energy (Figure 2.20). Particle sizes range from 1/16 – 256 mm, including pebbles and cobbles (Wentworth 1922). (Unique ID = 18)



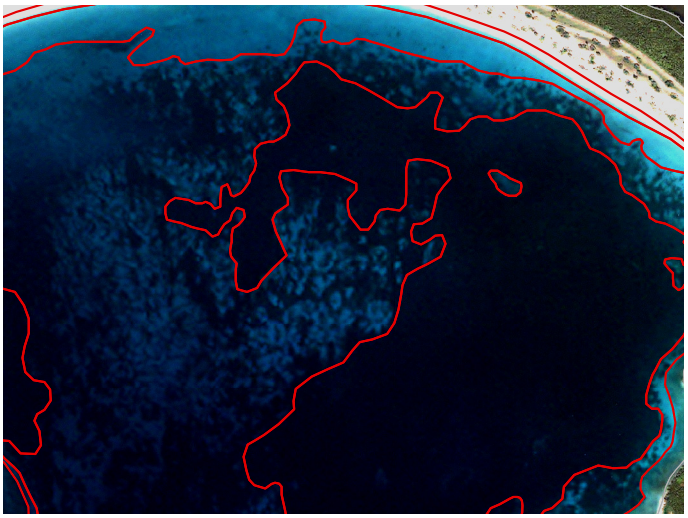


Figure 2.20. Depictions of *Sand* structure in Ensenada Sombe in Vieques. The features outlined by a red polygon include Sand with no biological cover (lighter), as well as with seagrass and algae (darker).

Mud

Fine sediment often associated with river discharge and build-up of organic material in areas sheltered from high-energy waves and currents (Figure 2.21). Particle sizes range from <1/256 – 1/16 mm (Wentworth 1922). (Unique ID = 19)

Figure 2.21. Depictions of *Mud* structure in Vieques. A red polygon outlines the features on satellite imagery.

Sand with Scattered Coral and Rock

Primarily sand bottom with scattered rocks or small, isolated coral heads that are too small to be delineated individually (i.e., smaller than individual patch reef) (Figure 2.22). If the density of small coral heads is greater than 10% of the entire polygon, this structure type is described as *Aggregated Patch Reefs*. (Unique ID = 20)

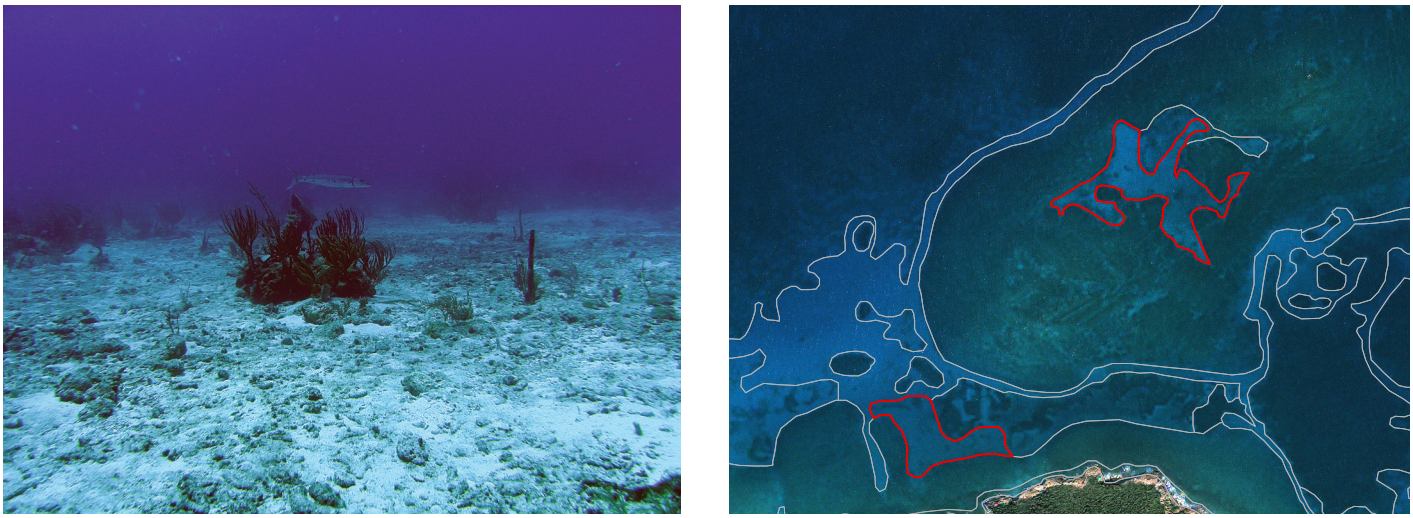


Figure 2.22. Depictions of *Sand with Scattered Coral and Rock* structure in Vieques. A red polygon outlines the features on satellite imagery.

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*. (Unique ID = 3)

Land

Terrestrial features at or near the spring high tide line. (Unique ID = 21)

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 2.23). (Unique ID = 22)

Figure 2.23. Depictions of the pier in Esperanza, an *Artificial* structure in Vieques. A red polygon outlines the feature on satellite imagery.

Unknown
Major structure indistinguishable due to turbidity, cloud cover, water depth, or other interference with an optical signature of the seafloor. (Unique ID = 9)

Unknown
Detailed structure indistinguishable due to turbidity, cloud cover, water depth, or other interference with an optical signature of the seafloor. (Unique ID = 99)

Biological Cover Classes

Eighteen distinct and non-overlapping biological cover classes were identified that can be mapped through visual interpretation of remotely-sensed imagery. Cover classes refer only to the biological component colonizing the surface of the feature and does not address zone or structure type. Habitats or features that cover areas smaller than the MMU were not considered. The cover types are defined in a collapsible hierarchy ranging from seven major classes (*Algae, Seagrass, Live Coral, Mangrove, Coralline Algae, No Cover, Unclassified* and *Unknown*), combined with a modifier describing the distribution of the dominant cover type throughout the mapping unit (*10%-<50%, 50%-<90%, 90%-100%*).

It is important to reinforce that the modifier represents a measure of the level of patchiness of the biological cover at the scale of delineation and not the density observed by divers in the water. For example, a seagrass bed can be described as having 90%-100% biological cover, but have

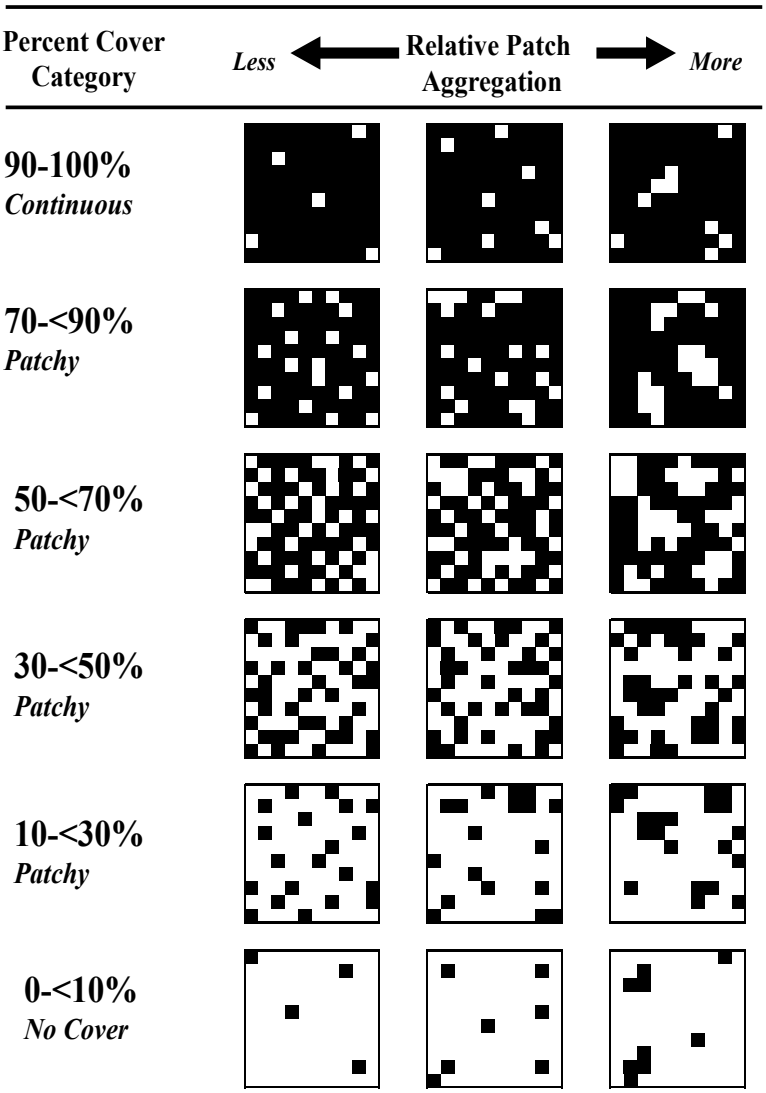


Figure 2.24. Guidance chart to aid visual interpreter's estimation of patchiness in assigning percent cover. Note that each large square denotes a minimum mapping unit.

sparse shoot densities when observed by divers. Figure 2.24 is a visual aid used by mappers to estimate of patchiness.

Major Cover

Algae
Substrates with 10% or greater distribution of any combination of numerous species of red, green, or brown algae. May be turf, fleshy or filamentous species. Occurs throughout many zones, especially on hard bottoms with low coral densities and soft bottoms in deeper waters on the *Bank/Shelf* zone (Figure 2.25). (Unique ID = 1)

Figure 2.25. Depictions of *Algae* dominated habitats. A red polygon outlines an algal-dominated feature in Puerto Ferro. Underwater pictures illustrate the different algal covers on unconsolidated sediment (middle) and hardbottom (right).

Seagrass
Habitat with 10% or more of the mapping unit dominated by any single species of seagrass (e.g., *Syringodium sp*., *Thalassia sp*., and *Halophila sp*.) or a combination of several species (Figure 2.26). (Unique ID = 2)

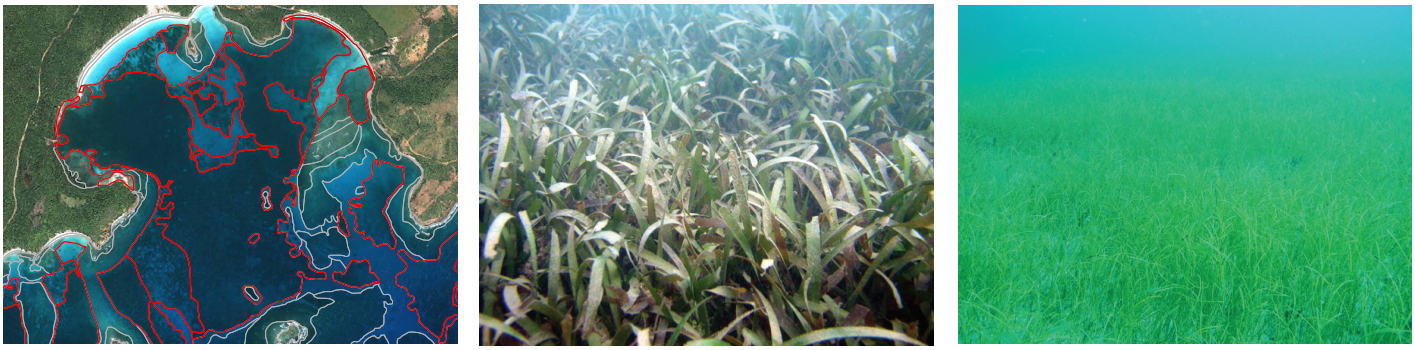


Figure 2.26. Extensive *Seagrass* beds, such as that in Bahia Salina del Sur, are prevalent around the island. A red polygon outlines the features on satellite imagery. Turtle Grass (*Thalassia testudinum*) (middle) and Manatee Grass (*Syringodium filiforme*) (right) are both common.

Live Coral
Substrates colonized with 10% or greater live reef building corals and other organisms including scleractinian (e.g., *Acropora sp.*) and octocorals (e.g., *Briareum sp.*). This category is rare in the U.S. Caribbean and was absent in Vieques. (Unique ID = 3)

Mangrove

Mangrove habitat is comprised of semi-permanently, seasonally or tidally flooded mangrove vegetation formations that grow near the sea (Figure 2.27). Mangrove trees are halophytes; plants that thrive in and are especially adapted to salty conditions. In Puerto Rico 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 mangrove grows at the water's edge and in the tidal zone. Black mangrove and white mangrove grow further inland in areas where flooding occurs only during high tides. Generally found in areas sheltered from high-energy waves. This habitat type is usually found in the *Shoreline Intertidal* zone. (Unique ID = 4)

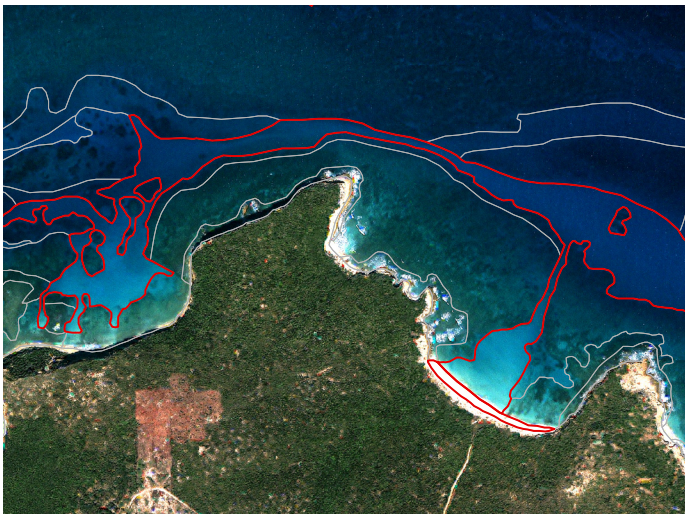
Figure 2.27. Depictions of *Mangrove* cover in Ensenada Honda. A red polygon outlines the features on satellite imagery.

Coralline Algae

An area with 10% or greater coverage of any combination of numerous species of encrusting or coralline algae. May occur along the reef crest, in shallow back reef, and within the bank/shelf zone. Broad enough coverage to constitute dominant biological cover in a MMU is rare in the U.S. Caribbean. (Unique ID = 5)

No Cover

Substrates not covered with a minimum of 10% of any of the other biological cover types. This habitat is usually found on sand or mud bottoms. Overall, *No Cover* is estimated at 90%-100% of the bottom with the possibility of some very low density biological cover (Figure 2.28). (Unique ID = 6)



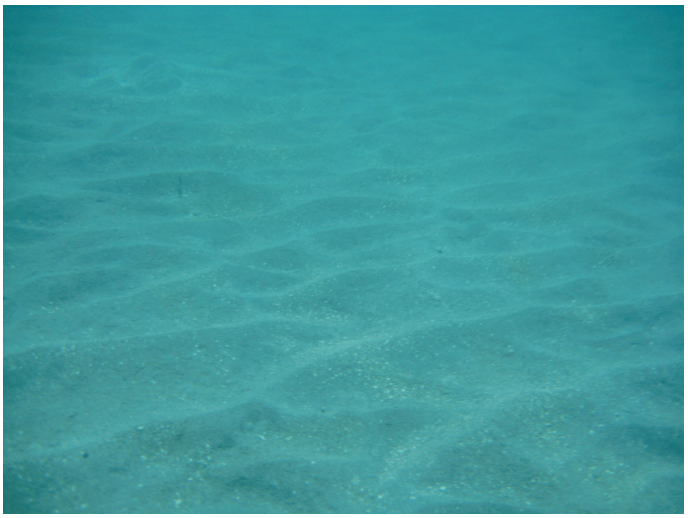


Figure 2.28. Depictions of features with *No Cover* on the northeast shore of Vieques. A red polygon outlines the features on satellite imagery.

Unclassified
A different biological cover type, such as upland, deciduous forest, that is not included in this habitat classification scheme. Most often used on polygons defined as *Land* with terrestrial vegetation. (Unique ID = 7)

Unknown
Biological cover is indistinguishable due to turbidity, cloud cover, water depth, or other interference with an optical signature of the seafloor. (Unique ID = 9)

Percent Major Cover

Patchy 10% - <50%
Discontinuous cover of the major biological type with breaks in coverage that are too diffuse to delineate or result in isolated patches of a different dominant biological cover that are too small (smaller than the MMU) to be mapped as a different feature. Overall cover of the major biological type is estimated at 10% - <50% of the polygon feature (Figure 2.29). (Unique ID = 2)

Patchy 50% - <90%
Discontinuous cover of the major biological type with breaks in coverage that are too diffuse to delineate or result in isolated patches of a different dominant biological cover that are too small (smaller than the MMU) to be mapped as a different feature. Overall cover of the major biological type is estimated at 50% - <90% of the polygon feature (Figure 2.29). (Unique ID = 3)

Continuous 90% - 100%
Major biological cover type covering 90% or greater of the substrate (Figure 2.29). May include areas of less than 90% major cover on 10% or less of the total area that are too small to be mapped independently (less than the MMU). (Unique ID = 4)

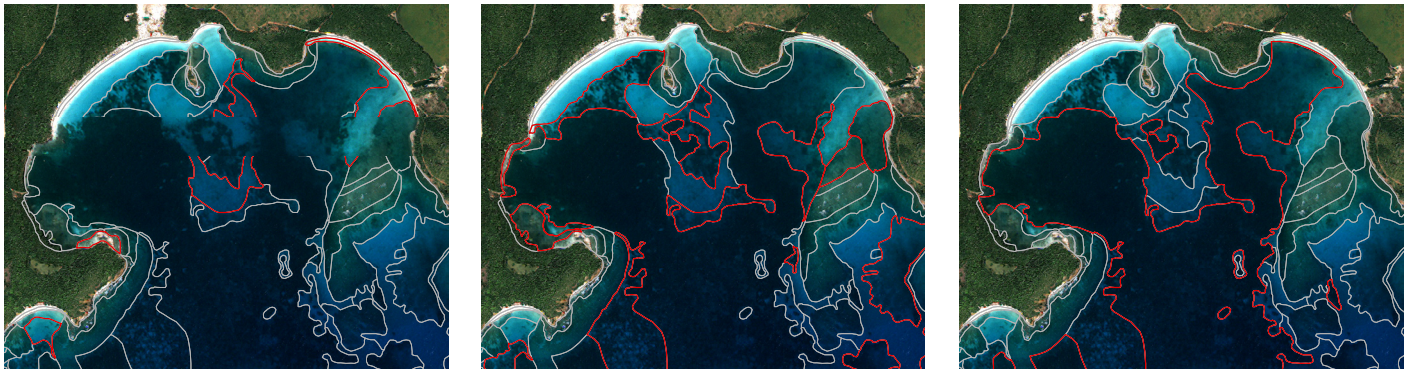


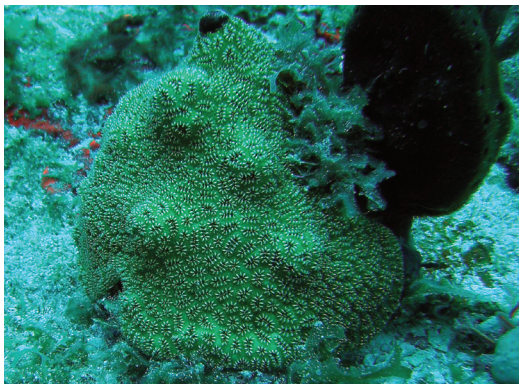
Figure 2.29. Representation of the three percent major cover modifiers (left to right: *10% - <50%, 50% - <90%, 90% - 100%*) using a seagrass bed in Bahia Salina del Sur as an example. Red polygons outline the features on satellite imagery.

Not Applicable
An estimate of percent cover is not appropriate for this particular major biological cover class. Regularly accompanies the use of *Unclassified* as the major biological cover. (Unique ID = 5)

Unknown
Percent estimate of the biological cover is indistinguishable due to turbidity, cloud cover, water depth, or other interference with an optical signature of the seafloor. (Unique ID = 9)

Live Coral Cover Classes

Four distinct and non-overlapping percent live coral classes were identified that can be mapped through visual interpretation of remotely-sensed imagery and ground-truthing. This attribute is an additional biological cover modifier used to maintain information on the percent cover of live coral, both scleractinian and octocorals (Figure 2.30), even when it is not the dominant cover type. In order to provide resource managers with additional information on this cover type of critical concern, four range classes were used (0% - <10%, 10% - <50%, 50% - <90%, 90% - 100%). Distinction of scleractinian coral versus octocoral (i.e., hard versus soft coral) was



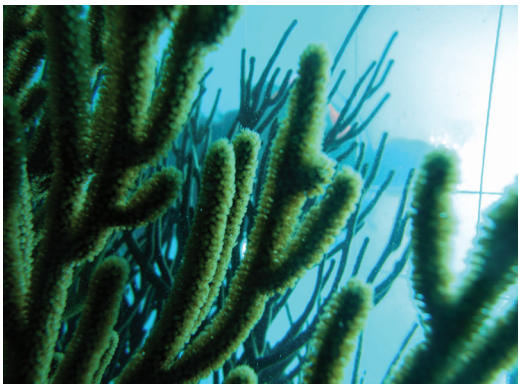


Figure 2.30. Both scleractinian (top) and octocorals (bottom) are considered when defining live coral cover.

limited by the current state of remote sensing technology and could not be separated in the Live Coral Cover modifier.

Live coral cover describes the percent coverage on hardbottom features at a fine-scale (i.e., diver scale), not the distribution at the scale of delineation, as was the case for dominant biological cover. For this reason, extensive *in situ* data is necessary. The observation was approximately 1 m to 3 m off the bottom feature and its associated field of view. As a result of these varying scales of interpretation, the percent biological cover and percent live coral cover modifiers are not additive properties within the same mapping unit. In many cases, they will sum to greater than 100%. For example, an aggregate reef can have continuous (90%-100%) cover of algae throughout a mapping unit, as well as 10%-50% density of coral at the fine-scale. Also, Percent Live Coral Cover refers only to the hardbottom component of any mapped polygon. For instance, an area of sand with some scattered coral and rock in it could be classified as 10% - <50% live coral cover even though 90% of the polygon is bare sand.

0% - <10%
Live coral cover of less than 10% of hardbottom substrate observed from 1-3 meters above the seafloor (Figure 2.31). (Unique ID = 1)

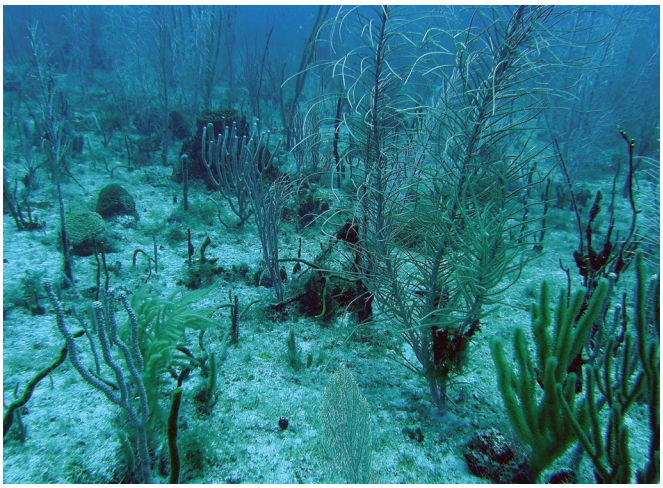
10% - <50%
Live coral cover between 10% and 50% of hard bottom substrate observed from 1-3 meters above the seafloor (Figure 2.31). (Unique ID = 2)

50% - <90%
Live coral cover between 50% and 90% of hard bottom substrate observed from 1-3 meters above the seafloor. (Unique ID = 3)

90% - 100%
Continuous live coral consisting of 90% or greater cover of the hard bottom substrate observed from 1-3 meters above the seafloor. (Unique ID = 4)

Not Applicable
An estimate of percent live coral cover is not appropriate for this particular feature. Regularly occurs in areas describing the terrestrial environment. (Unique ID = 5)

Unknown
Percent estimate of coral cover is indistinguishable due to turbidity, cloud cover, water depth, or other interference with an optical signature of the seafloor. (Unique ID = 9)



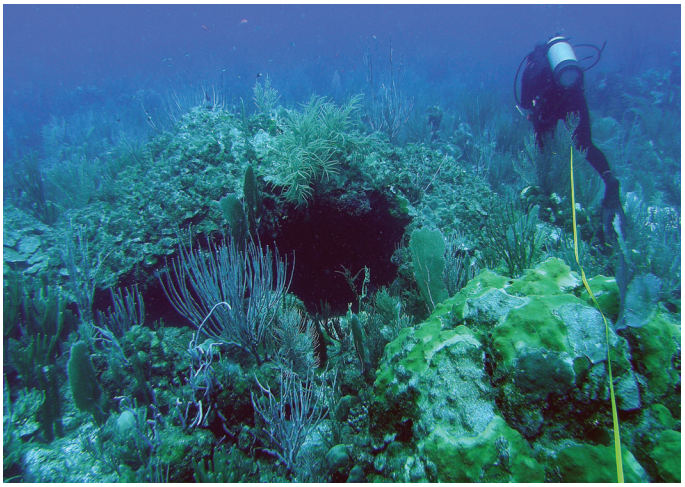


Figure 2.31. Illustration of live coral in the 0<10% (left), and 10% - 50% (right) cover range.

Percent Hardbottom Classes

An additional modifier was attributed to all polygons (except Land) to describe the percentage of hardbottom within that polygon. Several of the detailed structure types are heterogeneous in nature (e.g., *Aggregated Patch Reefs*, *Pavement w/ Sand Channels*, *Spur and Groove*), and the purpose of this modifier was to provide additional information about these structure types. It is expected that this will be useful in field survey planning when knowledge of the likelihood of encountering reef/hardbottom in an area is desired, or in estimating the actual amount of hardbottom in a polygon or mapped area. As with percent cover, Figure 2.24 was used as an aid to estimate the percent hardbottom in a polygon.

0% - <10%
Less than 10% of the structure within the polygon is hard substrate. All polygons attributed as *Unconsolidated Sediment* would have this designation. (Unique ID = 1)

10% - <30%
Hardbottom substrate between 10% and 30% of the polygon. (Unique ID = 2)

30% - <50%
Hardbottom substrate between 30% and 50% of the polygon. (Unique ID = 3)

50% - <70%
Hardbottom substrate between 50% and 70% of the polygon. (Unique ID = 4)

70% - <90%
Hardbottom substrate between 70% and 90% of the polygon. (Unique ID = 5)

90% - <100%
Hardbottom substrate between 90% and 100% of the polygon. (Unique ID = 6)

Not Applicable
An estimate of percent hardbottom is not appropriate for this particular feature. Regularly occurs in areas describing the terrestrial environment. (Unique ID = 7)

Unknown
Percent estimate of hardbottom is indistinguishable due to turbidity, cloud cover, water depth, or other interference with an optical signature of the seafloor. (Unique ID = 9)

2.3 MAP CREATION

Benthic habitat maps of the nearshore marine environment of Vieques, Puerto Rico were created by visual interpretation of remotely sensed imagery. Remotely sensed imagery, including IKONOS satellite imagery and color orthophotography, proved to be an excellent source from which to derive the edges, extent and attributes of marine habitats. Boundaries of features were delineated on digital imagery using a Geographic Information System (GIS) and a custom extension to ArcGIS 9.3 that enabled easy attribution of bottom features. Field investigations were conducted from small marine vessels in order to ground validate the spectral signature created by the myriad of submerged features of the marine environment. Once digital maps were produced, an assessment of thematic map accuracy was conducted.

General Mapping Approach

NOAA's approach to benthic habitat mapping of coral reef ecosystems was a six-step process:

1. Imagery Acquisition – The first step in map creation was the acquisition and processing of a comprehensive dataset of remotely sensed imagery. All imagery was geo-positioned to ensure acceptable spatial accuracy in the mapping product. In the case of Vieques two separate data types were used (IKONOS satellite imagery and color orthophotography) in order to capture the full mappable extent using optical techniques.

2. Habitat Boundary Delineation – A draft benthic habitat map was generated by delineating all features that could be identified by visual inspection of the remotely sensed imagery. During the creation of this first draft, the interpreter placed discrete points on the map that were difficult to distinguish and that warranted field investigation. These sites were referred to as "ground validation" positions.

3. Ground Validation – NOAA field scientists explored the ground validation locations with a suite of assessment techniques depending on the conditions at each site. A combination of underwater video, free diving, snorkeling and surface observations were used to survey the ecological characteristics at each location. This information was analyzed and the initial maps were edited to generate a second draft map.

4. Expert Review – The second draft map was then distributed to local marine biologists, resource managers, and other experts for review. Comments were integrated into the map products to generate a third draft map.

5. Accuracy Assessment – Field investigations were conducted at pre-defined locations to assess the accuracy of the third draft map. Locations were generated with a stratified random sampling design that allowed for a statistically rigorous assessment of map accuracy. An independent NOAA scientist, not associated with map creation, classified the video and conducted the analysis.

6. Final Products Creation – A final benthic habitat map for Vieques was generated by correcting inaccuracies identified by the accuracy assessment. Additionally, all associated datasets, including GIS files, field video and metadata were packaged and provided to project partners and the public.

Imagery Acquisition

Remote sensing imagery is a valuable tool for natural resource managers and researchers since they provide an excellent record of the location and extent of seafloor habitats. Generally, feature detection of seafloor habitats was possible from the shoreline to water depths of approximately 30 meters, depending on water clarity.

IKONOS satellite imagery provides precise and robust data with spectral and spatial resolution suitable for shallow water benthic mapping. Furthermore, satellite imagery provides efficient and effective global coverage for repeated imaging of remote islands that are often obscured by cloud cover. Ten scenes (Table 2.1) were obtained for the area extending approximately 3 nm from the shoreline of Vieques. The IKONOS satellite, owned and operated by GeoEye, provides commercially available panchromatic (black and white) and multispectral (blue/green/red/near-infrared) imagery. The panchromatic imagery has a 1 m pixel dimension and the multispectral imagery has a 4 m pixel dimension. The IKONOS imagery was acquired in 11 km wide swaths that are mosaicked together to produce complete images of locales.

Table 2.1. Acquisition dates of IKONOS satellite imagery used for creation of the Vieques benthic habitat map.

IMAGE ID	ACQUISITION DATE
215365_0000000	11/1/2006
215365_0040000	11/12/2006
215365_0070000	11/23/2006
215365_0120000	12/4/2006
215510_0000000	12/18/2006
244220_0000000	11/23/2007
244220_0010000	11/23/2007
255604_0000000	1/9/2008
259852_0040000	12/18/2007
260684_0010000	1/28/2008

The following four processing steps were completed for each IKONOS image and are described in detail in subsequent text:

1. Geo-positioned with satellite ephemeris data and supplemental ground control,

2. Corrected for terrain displacement,

3. Pan-sharpened, and

4. Removed sun glint.

Figure 2.32. Geodetic marker from NOAA's National Geodetic Survey that was used as a ground control point.

Geo-referencing of the imagery was performed using PCI OrthoEngine module. Fixed ground features visible in the IKONOS imagery (Figure 2.32) were selected for ground control points (GCPs) to be used in geo-referencing the imagery (i.e., to link the image pixels to a real world coordinate system). NOAA scientists occupied multiple locations throughout Vieques using L1 Trimble GeoXT mapping grade GPS. GPS observations were adjusted using the continuously-operating base station (VITH CORS) located in St. Thomas, USVI. NOAA obtained points with a wide distribution throughout the imagery whenever possible. Only ground control points for terrestrial features were collected due to the difficulty of obtaining precise positions for submerged features. Image to image tie-points were used to further co-register the imagery with other better positioned scenes. Tie points are distinct features, such as street intersections, piers, coral heads, reef edges, and bridges, which were visible in overlap areas of each image. These features were precisely aligned between scenes, thus providing exterior orientation control to co-register the scene.

Terrain displacement was corrected for the orthrectification bundle adjustment using the U.S. Geological Survey's Digital Elevation Model (DEM) (Figure 2.33).

PCI OrthoEngine Pansharpening module was employed to create a high-resolution color image to be used for visual interpretation by NOAA scientists. Pan-sharpening, also known as image fusion, is the concept of compiling multiple images into a composite product, which maintains the spectral signatures of the input color images while enhancing the spatial features with the input panchromatic image. It was applied to the IKONOS imagery to increase the spatial resolution of the 4 m multispectral data to the panchromatic data resolution of 1 m.

In addition, image enhancements were conducted on the positioned and pan-sharpened imagery to remove specular reflection from the sea surface. Reflection of solar radiation on non-flat water surfaces often results in areas of bright white sun glint in remotely sensed imagery. Typically, sun glint forms bands of white along wave edges on the windward side of nearshore environments. Sun glint can obscure bottom features and should be removed before habitat delineation. The method for removal of sun glint described in Hedley et al. (2005) was applied to the IKONOS imagery.

True-color (red/green/blue) and false-color (near-infrared) digital orthophotos for Vieques, PR, was the secondary imagery source used for delineating benthic habitats. Imagery was collected by 3001, Inc. under contract to the U.S. Army Corps of Engineers, in September and October of 2007 to produce orthophotos with a one foot ground sample distance (GSD). Flight height was maintained at 8,650 ft above ground level throughout the acquisition effort and was collected at 30% sidelap. For a more complete description of the product see the metadata report included with the project deliverables. As the data were collected primarily for terrestrial purposes, the coverage of the marine environment varied between photos. However, the high-resolution imagery was often very useful for delineating nearshore features.

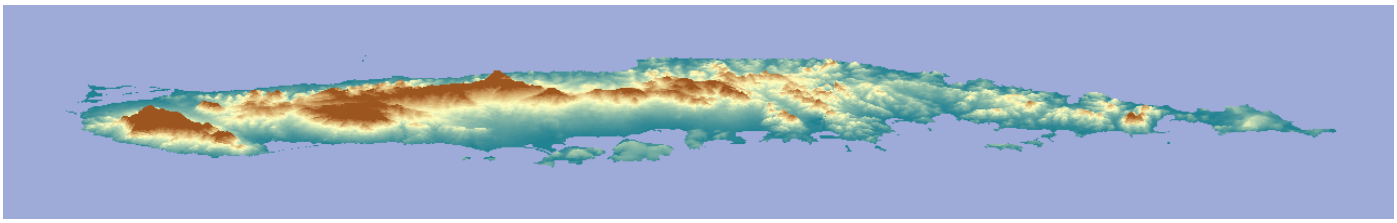


Figure 2.33. Oblique view of U.S. Geological Survey's Digital Elevation Model used to correct terrain displacement during orthorectification process.

Habitat Boundary Delineation and Attribution

As described by BAE Systems (2007), traditional methods of stereoplotter digitizing of photo interpreted habitat classes have gradually been replaced by the increased access and functionality of GIS software for on-screen "heads up" digitizing. GIS-based techniques have several distinct advantages, including:

- Elimination of intermediate steps required to go from hardcopy to digital maps, which reduces slight distortions in habitat boundaries,
- Enhanced productivity in map creation due to gained efficiency,
- Development of a dynamic link between habitat delineations and the associated attributes in a database, and
- Increased analytical capabilities through the use of spatial analysis routines in the GIS.

The Vieques benthic habitat map and mapping methods were developed using ESRI's ArcGIS 9.3 (ESRI 2008) and an ArcGIS extension created by NOAA, the Habitat Digitizer Extension (Buja 2008a). The Habitat Digitizer Extension is a GIS tool designed to use a hierarchical classification scheme to delineate features by visually interpreting geo-referenced images. The extension allowed the interpreter to create the custom classification scheme described in section 2.2, digitize polygons using standard ArcGIS editing tools, and attribute the features using a dialog containing the created scheme. The extension allowed for rapid delineation and attribution of polygons, which significantly improved the efficiency of map creation.

The Habitat Digitizer Extension allowed several critical digitizing parameters to be set in advance in order to standardize the map output. The Minimum Mapping Unit (MMU) restriction was set to 1,000 m² (~0.25 acre). In contrast, NOAA's previous map of PR and the USVI was created with a one acre MMU (Kendall et al. 2001). This reduction was in response to the coral reef management community's interest in having finer resolution maps to make resource management decisions with. However, there were still features visible in the imagery, such as patch reefs, which were smaller than the MMU and were not included as individual features in the map.

The digitizing scale was set to 1:4,000.The interpreter was allowed to zoom in and out to varying scales when assessing an area, but always returned to 1:4,000 before boundary delineation. Qualitative experimentation results adapted from Kendall et al. (2001) indicated that digitizing at this scale optimized the tradeoff between positional accuracy of lines and time spent digitizing. In general, line placement conducted while zoomed in at fine scales results in excellent line accuracy and detail, but can be quite time consuming. Conversely, while zoomed out, lines can be drawn quickly but lack both detail and positional accuracy. In addition, the resolution of the imagery often influences the digitizing scale. For example, when zooming in on a feature, there becomes a scale at which the feature becomes less distinct. Although the smaller pixel size of the orthophotos could have allowed mapping at a finer scale, as in Zitello et al. 2009, who used a 1:2000 scale, 1:4000 was more appropriate for the lower resolution IKONOS imagery.

Habitat boundary delineation and attribution techniques were adopted from Kendall et al. (2001). Using the Habitat Digitizer, habitat boundaries were delineated around spectral signatures of particular color and texture patterns in the remotely sensed imagery that corresponded to habitat types in the classification scheme described in Section 2.2. (Figure 2.34). This was often accomplished by first digitizing a large boundary polygon such as the habitats that compose the shoreline and then appending new polygons to the initial boundary polygon. Another technique was to draw one large polygon around a feature of similar type and then split it down into smaller polygons, an approach often used for seagrass beds of varying patchiness. It was believed that the positional accuracy of polygon boundaries was similar to that of the source imagery since delineations were performed directly on the remotely sensed imagery.

Brightness, contrast and histogram stretching of the source imagery were often manipulated in ArcGIS to enhance the interpretability of some subtle features and boundaries. This was particularly helpful in deeper water where differences in color and texture between adjacent features tend to be more subtle and boundaries more difficult to detect. Particular caution was used when interpretation was performed from altered images, since results from color and brightness manipulations can sometimes be misleading. Additional ancillary datasets were consulted to improve the understanding of particular areas. These data types included previously-com-

pleted habitat maps (Kendall et al. 2001), bathymetry, nautical charts, and imagery from different time periods.

Ground Validation

The creation of high-quality benthic habitat maps requires field work to enhance accuracies of habitat attribution and habitat delineation. Following the generation of an initial draft benthic habitat map, a team of NOAA scientists explored selected field locations to verify habitat type. These "ground validation" (GV) sites were targeted by the interpreter to satisfy one of the following two objectives:

1. Explore areas in the imagery with confusing or difficult to determine spectral signatures, or

2. Establish a transect moving from land to sea to better understand habitat transitions in a given area. These transects are important because a single habitat type may provide a different signature depending on water depth and sea state.

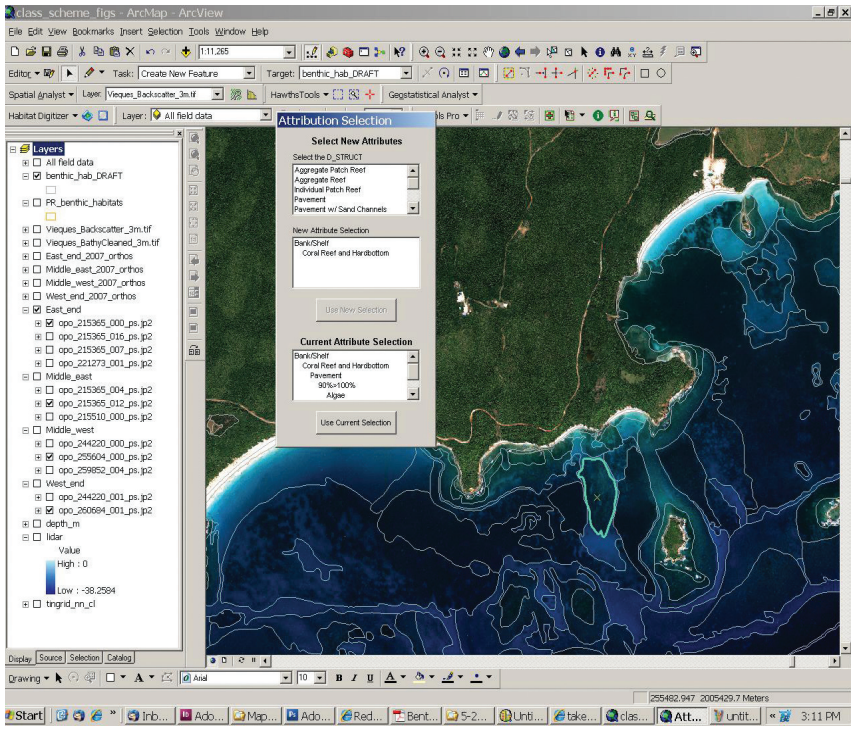


Figure 2.34. NOAA Biogeography Branch's Habitat Digitizer Extension (Buja 2008a) was used to attribute map polygons with all components of the habitat classification scheme.

Numerous GV locations were selected while the photo interpreter was generating the draft habitat map. Geographic coordinates were extracted for these sites and uploaded into Garmin GPS 76 WAAS-enabled handheld devices. Data were collected on 141 GV sites (Figure 2.35) over a one-week field mission from October 7-13, 2008 (Section 2.4).

The boat captain maneuvered the vessel to within 5 m of the target location and made every effort to maintain that location without jeopardizing crew and equipment safety. Once on site, NOAA scientists would simultaneously deploy a SeaViewer Sea-Drop 950 camera and begin logging a waypoint on a Trimble GeoXT GPS receiver. The drop camera reached the bottom in approximately 5 - 10 seconds and bottom imagery was recorded to mini-digital video tapes using a Sony Walkman video recorder. The camera operator adjusted the camera position to get a downward view at approximately 2 m from the bottom and a side view of the habitat at each location. This allowed for accurate measurements of percent biological cover and a broader sense of the structure at each site. No attempt was made to standardize the amount of bottom time the camera would capture in order to avoid the confusion of viewing multiple habitat types. In fact, it was often advantageous for the vessel to drift across habitat transitions, thus allowing the interpreter to understand the ecotone at many locations. Position logging in the Trimble receiver was optimized to plot every epic (i.e., position) along a waypoint. This allowed for accurate depiction of the vessel's drift line at a single GV location and was utilized in subsequent assessment of the data.

While the video camera was recording, an observer viewed the video real-time on a Panasonic Toughbook aboard the survey vessel. They categorized each site according to the levels of the habitat classification scheme: major and detailed geomorphological structure, major biological cover, percent major biological cover and percent coral cover. Data was entered into a custom data dictionary generated in Trimble Pathfinder Office software and loaded onto the Trimble data logger. Field sheets representing an exact replicate of the digital data dictionary were also populated as back-up to the digital classification information.

Of the 141 sites occupied during ground validation, 123 were assessed with the underwater drop camera. Shallow, nearshore sites that were inaccessible by the survey vessel were surveyed by snorkel. Sites were categorized in the same way, but in lieu of drop camera video, a digital camera in an underwater housing was used to take pictures. Mangrove target locations were generally assessed from the boat after approaching the

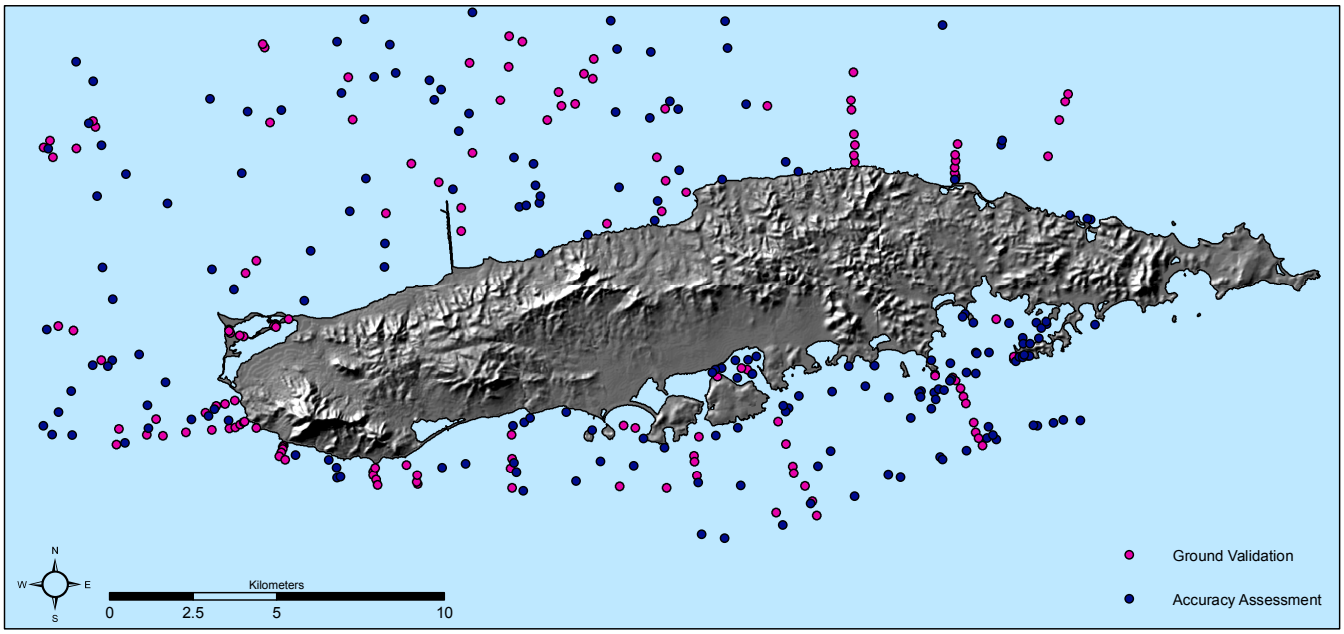


Figure 2.35. Spatial distribution of the 141 ground validation and 185 accuracy assessment sites visited during the October 2008 mission.

target as close as possible, and were again documented with digital pictures. Additional mangrove locations were approached by road.

Trimble Pathfinder Office software was used to post process and differentially correct the raw GPS data to the Continually Operating Reference System (CORS) station at St. Thomas, U.S. Virgin Islands (VITH). Videos were converted to digital video clips using Final Cut Pro software and reviewed. Precise GPS positions and the associated classification data were viewed in a GIS to enhance the accuracy of the draft benthic habitat map. Polygon boundaries and habitat classifications were revised where field data necessitated changes.

GIS Quality Control

All GIS deliverable products generated throughout the mapping process were closely examined for error. Particular attention was given to polygon geometry of the benthic habitat map and attribution of both the habitat map and GV and AA field GIS datasets. Multipart, sliver and void polygons were all removed using standard ArcGIS Spatial Analyst tools. Two custom ArcGIS extensions were employed to identify the following conditions:

1. Adjacency – polygons that shared a common boundary and exact attribute combination that were delineated separately (Buja 2008b),

2. Overlap – polygons sharing the same geographic space, thus violating mutual exclusion (Buja 2008c).

Errors resulting from either of these GIS routines were corrected on draft maps and eliminated in the final product.

A review of habitat boundaries by a NOAA staff member not involved in imagery interpretation concluded that all areas mapped as *Unknown* were indeed indistinguishable on the source imagery.

A visual inspection of attributes on a feature-by-feature basis was conducted to correct for any misspellings or illogical attribute combinations. These types of errors were minimal; as the use of the Habitat Digitizer Extension standardized the process of populating GIS attribute tables. In the rare instances where manual attribution was required, particular attention was given to control these processes. The aforementioned visual inspection accounted for any potential errors.

GIS data from this work were determined to be topologically clean and free of attribution errors. In addition, metadata summaries were prepared in an FGDC-compliant format for all GIS products that were supplied during final delivery.

2.4 ACCURACY ASSESSMENT

Thematic accuracy of the Vieques benthic maps was characterized for major and detailed geomorphological structure, major and detailed biological cover, percent hardbottom and percent coral cover.

Collection of Field Data

Sites for the accuracy assessment procedure were determined through a stratified random sampling technique. Funding and logistical constraints indicated that 185 sites could be included (Figure 2.35). Points were initially distributed based on the proportion of area occupied by each of the 12 detailed structure categories in a draft benthic map of Vieques. Classes that covered a large proportion of the total area but are easy to interpret had some points redistributed to other bottom classifications. For example, sand comprised ~60% of the mapped area and could therefore have received 60% of the assessment effort. Experience has shown, however, that *Sand* is relatively easily and accurately mapped (>90% correct, Battista et al. 2007a; Walker and Foster 2009; Zitello et al. 2009). Therefore, the assessment effort was redistributed to other important bottom types that covered less area. For example, *Aggregate Reef* covered only 4% of the mapped area and therefore initially only received 4% or 7 of the 185 available survey points. Survey effort was raised to 20 points to more adequately assess this scientifically and ecologically important bottom type. Points were randomly placed within each class at a minimum distance of 50 m apart to minimize potential overlap among survey sites.

Data were collected during a one-week field mission from October 6-13, 2009. Navigation to sample locations was conducted using GPS. Underwater video was taken at each site, provided the location was safely accessible by the survey vessel. Video length depended on the habitat type and vessel drift and ranged from approximately 30 seconds to two minutes. Videos of large, homogeneous sand habitats were generally short while heterogeneous hardbottom habitats, especially edges, were typically longer. While the video was being recorded, a string of GPS waypoints were recorded on board the vessel. At least three positions were logged at each site, but this number was generally much higher and depended on the satellite signal, length of the video clip, current speed, and vessel drift. This resulted in a string of positions that tracked boat movement at each site. Video at each site was categorized for major/detailed geomorphological structure, major/detailed biological cover, percent hardbottom, and percent coral cover.

Very shallow, nearshore sites were often not accessible by the survey vessel and video camera system and therefore were surveyed using snorkeling gear and a digital camera. Mangrove sites were generally assessed from the boat or land after approaching the target as close as possible.

Evaluation of Assessment Data

The GPS positions were determined to have a positional accuracy of < 1 m for most points. For each survey site, multiple GPS positions were combined to generate an “average” GPS point. The GPS data were then exported and plotted in ArcGIS along with the corresponding field notes. In most cases, the average point was a sufficient representation of the survey site; however in some cases vessel drift caused the survey to cross polygon edges. In these cases, the “average” survey point was shifted to the portion of the transect and polygon that was intended to be assessed.

Each video clip or digital picture was viewed in concert with the benthic habitat map and the remote sensing imagery of each site. All analysis at this stage was made by a photointerpreter independent of the scientist who created the benthic map. Patchiness of the biological cover was assessed at the polygon level, and hence it was often necessary to adjust the classifications that were initially recorded in the field to reconcile the differences between the video and map scales. For example, a site may have been classified as continuous seagrass based on the video clip alone, but if the patchiness of the polygon in which the site occurred was actually only 50% - <90% upon examination of the imagery, the patchiness for the survey point was changed to 50% - <90%. 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, ad-

ditional 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*.

Following these adjustments, the map classification underlying each point was extracted. Sites that differed between field notes and map classification were further evaluated both in GIS and from video to determine possible sources of disagreement. At this stage, mismatches between GPS and map attributes that were a product of the differences in scale between the video data and imagery rather than errors in classification were identified. For example, there were several occurrences where the survey video documented *Sand* with no cover, but the point was located within a heterogeneous polygon that was mapped as sand with patchy *Seagrass* or *Algae*, *Sand with Scattered Coral and Rock*, or *Aggregated Patch Reefs* that could only be perceived at the broad scale of the remote sensing imagery. For these cases, the points were only classified for structure based on both the video and imagery. Since the mapped polygon cover was not observed in the accuracy assessment video, they were not included in the assessment of biological cover.

Percent coral cover was classified for both hardbottom and softbottom habitats; however it is defined as the percent coral cover on the hardbottom substrate within that polygon (see Section 2.2). If a site was determined to be located within a hardbottom polygon but no hardbottom was seen in video (e.g., *Aggregated Patch Reefs*), coral cover could not be sufficiently assessed at that site. Hence, such sites were not included in the error matrix for percent coral cover.

Following this process, 185 points were included in the accuracy assessment analysis for major structure, 182 for detailed structure, 183 for major biological cover and detailed biological cover, 185 for percent hard bottom, and 185 for percent coral cover.

Analysis of Thematic Accuracy

The thematic accuracy of the Vieques benthic habitat map was characterized in several ways from these data. Error matrices were computed for the attributes major and detailed geomorphological structure, major and detailed biological cover, percent hard bottom, and percent coral cover. Overall accuracy, producer's accuracy, and user's accuracy were computed directly from the error matrices (Story and Congalton 1986). The error matrices were constructed as a square array of numbers arranged in rows (map classification) and columns (accuracy assessment, or ground-truthed classification). 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 is a measure of how well the mapper 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 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 cell in the matrix was divided by the column total (n_{i-}) to yield a producer's accuracy and by the row total (n_{-j}) to yield a user's accuracy.

In addition, the Tau coefficient (T_e), a measure of the improvement of classification accuracy over a random assignment of map categories, was calculated. As the number of categories increases, the probability of random agreement (Pr) diminishes, and T_e approaches P_o. See Ma and Redmond (1995) for mathematical equations.

Redistribution of sampling effort caused rare but important map categories to be sampled at a greater rate than common map categories. For example, although Sand habitat comprised 60% of the map area, only 25% of the target points were allocated for this habitat. Conversely, *Aggregate Reef* comprised only 4% of the map area, but received 11% of the allocated target sample points. Such allocation is necessary for reasonable assessment of individual map categories but introduced bias when assessing overall accuracy (Hay 1979; Card 1982). The bias introduced by differential sampling rates was removed using the method of Card (1982), which utilizes the proportional areas of each map category relative to the total map area. The category proportions were also utilized in the computation of confidence intervals (CI) for the overall, producer's, and user's accuracies (Card 1982; Congalton and Green 1999). This approach was modeled after Walker and Foster (2009), who recently conducted an accuracy assessment of a benthic map of the Florida Keys.

The category proportions (π_j) were computed from the GIS layer of the draft benthic habitat map by dividing the area of each category by the total map area. Proportions were not computed for the percent coral cover matrix. Due to the way percent coral cover was estimated, doing so would have required an adjustment by the percent hardbottom, and there was insufficient sample size of all combinations of the percent coral and percent hardbottom categories. The individual cell probabilities were computed as the product of the original error matrix cell values and π_j, divided by the total number of assessment points per category ($n_{.j}$).

The relative proportions of the cell values within a row of the error matrix were unaffected by this operation, but the row total of a particular category now equaled the fraction of map area occupied by that category (π_j), instead of the total number of accuracy assessment points within it ($n_{.j}$). The estimated true proportions (p_i) of each map category given the observed classification errors were computed as the sum of individual cell probabilities down each column of the error matrix.

The π_j-adjusted overall and producer's accuracies were then computed from the new error matrix. The values of the π_j-adjusted overall and producer's accuracies differ by design from those of the original error matrix, as they have been corrected for the areal bias introduced by stratified random sampling and the effort redistribution 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 using the equations of Card (1982).

Accuracy Assessment Results and Discussion

Major Geomorphological Structure

Error matrices for major geomorphological structure are displayed in Table 2.2 for the simple tally of assessment points and 2.3 for the unbiased values of producers and overall accuracy corrected by category proportions. The overall accuracy (P_o) when calculated by a simple tally of correct points was 98.4% (Table 2.2). The Tau coefficient was 0.968 ± 0.036. Adjusted overall accuracy, corrected for bias using the map category proportions, was 99.1 (±0.0)% (Table 2.3). The user's and producer's accuracies were similarly high for both hard and softbottom habitats (Table 2.3).

Table 2.2. Error matrix for major geomorphological structure.

Map data (j) \ Accuracy Assessment (i)	Hard	Soft	$n_{.j}$	User's Accuracy (%)
Hard	**109**	3	112	**97.3%**
Soft		**73**	73	**100.0%**
$n_{i.}$	109	76	n=185	
Producer's Accuracy (%)	**100.0%**	**96.1%**	**P_o =**	**98.4%**
			T_e =	**0.968 ± 0.036**

Detailed Geomorphological Structure

Error matrices for detailed geomorphological structure are displayed in Table 2.4 for the simple tally of assessment points and 2.5 for the unbiased values of producers and overall accuracy corrected by category proportions. The overall accuracy (P_o) when calculated by a simple tally of correct points was 78.0%, with a Tau coefficient (T_e) of 0.760 ± 0.066 (Table 2.4). The adjusted overall accuracy, corrected for bias using the category proportions, was higher at 88.8 (±4.2)% (Table 2.5), because the classes that covered the most area were also the most correctly interpreted.

Table 2.3. Error matrix for major geomorphological structure, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category proportions.

Map data (j) \ Accuracy Assessment (i)	Hard	Soft	$\pi_{.j}$	User's Accuracy (%)	User's CI (±%)
Hard	**0.325**	0.009	0.334	**97.3%**	**3.1%**
Soft		**0.666**	0.666	**100.0%**	**0.0%**
p_i	0.325	0.675	π=1		
Producer's Accuracy (%)	**100.0%**	**98.7%**	**P_o =**	**99.1%**	
Producer's CI (±%)	**0.0%**	**1.5%**	**CI(±) =**	**0.0%**	

Accuracies for individual map categories must be interpreted cautiously due to the low sample sizes (<10 points). User's accuracy was above 70% for 7 of the 12 categories (Table 2.5). Categories with relatively low accuracies that were evaluated by an adequate number of points were *Individual Patch Reef* (42.9%) and *Sand with Scattered Coral and Rock* (61.5%). Both these categories had very large confidence intervals. *Individual Patch Reefs* were most often confused with *Pavement* due to the small and circular shape of some pavement patches on the NW side of Vieques. *Sand with Scattered Coral and Rock* was most often misclassified simply as *Sand*, a very similar bottom type that often occurs adjacent to areas

Table 2.4. Error matrix for detailed geomorphological structure.

Map data (j) \ Accuracy Assessment (i)	Aggregate Reef	Aggregated Patch Reefs	Individual Patch Reef	Spur and Groove	Pavement	Pav w/ Sand Channels	Rock/Boulber	Reef Rubble	Rhodolith	Sand w/ SCR	Sand	Mud	$n_{j\cdot}$	User's Accuracy (%)
Aggregate Reef	**14**			1	3	1	1						20	**70.0%**
Aggregated Patch Reefs		**5**			1								6	**83.3%**
Individual Patch Reef	1	1	**6**		5					1			14	**42.9%**
Spur and Groove				**2**			1						3	**66.7%**
Pavement	2	2			**36**	2	3	1					46	**78.3%**
Pav w/ Sand Channels	3				2	**4**				1			10	**40.0%**
Rock/Boulder							**5**						5	**100.0%**
Reef Rubble					1			**3**			1		5	**60.0%**
Rhodoliths									**3**				3	**100.0%**
Sand w/ SCR										**8**	5		13	**61.5%**
Sand											**40**	1	41	**97.6%**
Mud												**16**	16	**100.0%**
$n_{i\cdot}$	20	8	6	3	48	7	10	4	3	10	46	17	n=182	
Producer's Accuracy (%)	**70.0%**	**62.5%**	**100.0%**	**66.7%**	**75.0%**	**57.1%**	**50.0%**	**75.0%**	**100.0%**	**80.0%**	**87.0%**	**94.1%**	**P_o =**	**78.0%**

T_e = 0.760 ± 0.066

Table 2.5. Error matrix for detailed geomorphological structure, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category proportions.

Map data (j) \ Accuracy Assessment (i)	Aggregate Reef	Aggregated Patch Reefs	Individual Patch Reef	Spur and Groove	Pavement	Pav w/ Sand Channels	Rock/Boulber	Reef Rubble	Rhodolith	Sand w/ SCR	Sand	Mud	$\pi_{j\cdot}$	User's Accuracy (%)	User's CI (±%)
Aggregate Reef	**0.028**			0.002	0.006	0.002	0.002						0.0404	**70.0%**	**20.49%**
Aggregated Patch Reefs	0.000	**0.005**			0.001								0.0054	**83.3%**	**30.43%**
Individual Patch Reef	0.001	0.001	**0.008**		0.007					0.001			0.0186	**42.9%**	**26.45%**
Spur and Groove				**0.000**									0.0001	**66.7%**	**54.43%**
Pavement	0.005	0.005			**0.081**	0.005	0.007	0.002					0.1040	**78.3%**	**12.16%**
Pav w/ Sand Channels	0.006				0.004	**0.008**				0.002			0.0203	**40.0%**	**30.98%**
Rock/Boulder							**0.004**						0.0037	**100.0%**	**0.00%**
Reef Rubble					0.010			**0.030**			0.010		0.0494	**60.0%**	**43.82%**
Rhodoliths									**0.093**				0.0925	**100.0%**	**0.00%**
Sand w/ SCR										**0.030**	0.019		0.0488	**61.5%**	**26.99%**
Sand											**0.581**	0.015	0.5959	**97.6%**	**4.82%**
Mud												**0.021**	0.0208	**100.0%**	**0.00%**
$p_{i\cdot}$	0.040	0.010	0.008	0.002	0.109	0.015	0.013	0.032	0.093	0.033	0.610	0.035	π=1		
Producer's Accuracy (%)	**70.3%**	**43.7%**	**100.0%**	**1.7%**	**74.7%**	**55.4%**	**29.8%**	**92.9%**	**100.0%**	**89.9%**	**95.3%**	**58.8%**	**P_o =**	**88.8%**	
Producer's CI (±%)	16.8%	29.8%	0.0%	3.6%	14.1%	33.8%	20.2%	13.9%	0.0%	13.1%	3.4%	47.8%	**CI(±) =**	**4.2%**	

with scattered coral or rock. Four categories had low adjusted producer's accuracy but were evaluated by very few accuracy assessment points and confidence intervals were large (Table 2.5).

Major Biological Cover

Error matrices for major biological cover are displayed in Table 2.6 for the simple tally of assessment points and 2.7 for the unbiased values of producers and overall accuracy corrected by category proportions. The overall accuracy (P_o) when calculated by a simple tally of correct points was 91.3%, with a Tau coefficient (T_e) of 0.891 ± 0.051 (Table 2.6). The adjusted overall accuracy, corrected for bias using the map category proportions, was lower but well within acceptable limits at 81.9 (±8.4)% (Table 2.7).

User's accuracy was >95% for all major cover levels except for seagrass (67%). This was due to confusion with algal beds, a cover commonly intermixed with seagrass. Adjusted producers accuracy was >70% for all categories. Accuracy of mapped coral cover will be discussed in the section Percent Coral Cover.

Table 2.6. Error matrix for major biological cover.

Map data (j) \ Accuracy Assessment (i)	Algae	Live Coral	Mangrove	Seagrass	No Cover	$n_{\cdot j}$	User's Accuracy (%)
Algae	**120**	2		3	1	126	**95.2%**
Live Coral						0	**n/a**
Mangrove			**10**			10	**100.0%**
Seagrass	10			**20**		30	**66.7%**
No Cover					**17**	17	**100.0%**
$n_{i\cdot}$	**130**	**2**	**10**	**23**	**18**	n=183	
Producer's Accuracy (%)	**92.3%**	**0.0%**	**100.0%**	**87.0%**	**94.4%**	P_o =	**91.3%**
						T_e =	**0.891±0.051**

Table 2.7. Error matrix for major biological cover, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category proportions.

Map data (j) \ Accuracy Assessment (i)	Algae	Live Coral	Mangrove	Seagrass	No Cover	$\pi_{\cdot j}$	User's Accuracy (%)	User's CI (±%)
Algae	**0.4179**	0.0070		0.0104	0.0035	0.439	**95.2%**	**3.8%**
Live Coral						0.000	**n/a**	**n/a**
Mangrove			**0.0106**			0.011	**100.0%**	**0.0%**
Seagrass	0.1597			**0.3194**		0.479	**66.7%**	**17.2%**
No Cover					**0.0715**	0.071	**100.0%**	**0.0%**
$p_{i\cdot}$	0.578	0.007	0.011	0.330	0.075	π=1		
Producer's Accuracy (%)	**72.4%**	**n/a**	**100.0%**	**96.8%**	**95.4%**	P_o =	**81.9%**	
Producer's CI (±%)	**10.4%**	**n/a**	**0.0%**	**3.6%**	**8.8%**	CI(±) =	**8.4%**	

Detailed Biological Cover

Error matrices for detailed biological cover are displayed in Table 2.8 for the simple tally of assessment points and 2.9 for the unbiased values of producers and overall accuracy corrected by category proportions. The overall accuracy (P_o) when calculated by a simple tally of correct points was 73.8%, with a Tau coefficient (T_e) of 0.711 ± 0.070 (Table 2.8). The adjusted overall accuracy, corrected for bias using the map category proportions, was lower at 61.0 (±9.8)% (Table 9). This was primarily due to the confusion between seagrass and algae, primarily NW of Vieques, which covers a very large proportion of the total mapped area.

Percent Hardbottom

Error matrices for percent hardbottom are displayed in Table 2.10 for the simple tally of assessment points and 2.11 for the unbiased values of producers and overall accuracy corrected by category proportions. The overall accuracy (P_o) when calculated by a simple tally of correct points was 83.2%, with a Tau coefficient (T_e) of 0.799 ± 0.065 (Table 2.10). The adjusted overall accuracy, corrected for bias using the map category proportions, was 86.1 (±4.5)% (Table 2.11). Greatest sources of error were between adjacent categories (e.g., site mapped as 70-90% hardbottom was actually 90-100%).

Table 2.8. Error matrix for detailed biological cover.

Map data (j) \ Accuracy Assessment (i)	Algae 10% - <50%	Algae 50% - <90%	Algae 90% - 100%	Live Coral 50% - <90%	Mangrove 10% - <50%	Mangrove 50% - <90%	Mangrove 90% - 100%	Seagrass 10% - <50%	Seagrass 50% - <90%	Seagrass 90% - 100%	No Cover 90% - 100%	$n_{\cdot j}$	User's Accuracy (%)
Algae 10% - <50%	**7**	1										8	**87.5%**
Algae 50% - <90%	4	**23**	9	1				1			1	39	**59.0%**
Algae 90% - 100%		12	**64**	1					2			79	**81.0%**
Live Coral 50% - <90%				**0**								0	**n/a**
Mangrove 10% - <50%					**1**							1	**100.0%**
Mangrove 50% - <90%						**1**						1	**100.0%**
Mangrove 90% - 100%							**8**					8	**100.0%**
Seagrass 10% - <50%	1		1					**1**		1		4	**25.0%**
Seagrass 50% - <90%		3	2						**10**	5		20	**50.0%**
Seagrass 90% - 100%			3							**3**		6	**50.0%**
No Cover 90% - 100%											**17**	17	**100.0%**
$n_{i\cdot}$	12	39	79	2	1	1	8	2	12	9	18	n=183	
Producer's Accuracy (%)	**58.3%**	**59.0%**	**81.0%**	**0.0%**	**100.0%**	**100.0%**	**100.0%**	**50.0%**	**83.3%**	**33.3%**	**94.4%**	**P_o =**	**73.8%**

T_e = 0.711±0.070

Table 2.9. Error matrix for detailed biological cover, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category proportions.

Map data (j) \ Accuracy Assessment (i)	Algae 10% - <50%	Algae 50% - <90%	Algae 90% - 100%	Live Coral 50% - <90%	Mangrove 10% - <50%	Mangrove 50% - <90%	Mangrove 90% - 100%	Seagrass 10% - <50%	Seagrass 50% - <90%	Seagrass 90% - 100%	No Cover 90% - 100%	$\pi_{\cdot j}$	User's Accuracy (%)	User's CI (±%)
Algae 10% - <50%	**0.013**	0.002										0.015	**87.5%**	**23.4%**
Algae 50% - <90%	0.022	**0.129**	0.051	0.006				0.006			0.006	0.219	**59.0%**	**15.8%**
Algae 90% - 100%		0.031	**0.166**	0.003					0.005			0.205	**81.0%**	**8.8%**
Live Coral 50% - <90%												0.000	**n/a**	**n/a**
Mangrove 10% - <50%					**0.001**							0.001	**100.0%**	**0.0%**
Mangrove 50% - <90%						**0.003**						0.003	**100.0%**	**0.0%**
Mangrove 90% - 100%							**0.007**					0.007	**100.0%**	**0.0%**
Seagrass 10% - <50%	0.012		0.012					**0.012**		0.012		0.048	**25.0%**	**43.3%**
Seagrass 50% - <90%		0.043	0.029						**0.144**	0.072		0.289	**50.0%**	**22.4%**
Seagrass 90% - 100%			0.071							**0.071**		0.143	**50.0%**	**40.8%**
No Cover 90% - 100%											**0.071**	0.071	**0.0%**	**0.0%**
$p_{i\cdot}$	0.047	0.205	0.329	0.008	0.001	0.003	0.007	0.018	0.150	0.155	0.077	π=1		
Producer's Accuracy (%)	**27.2%**	**62.9%**	**50.5%**	**n/a**	**100.0%**	**100.0%**	**100.0%**	**68.0%**	**96.5%**	**45.9%**	**92.7%**	**P_o =**	**61.8%**	
Producer's CI (±%)	**11.6%**	**8.6%**	**4.1%**	**8.4%**	**n/a**	**n/a**	**0.0%**	**16.0%**	**14.8%**	**6.2%**	**13.0%**	**Ci(±) =**	**9.8%**	

Percent Coral Cover

The error matrix for percent coral cover is displayed in Table 2.12. The overall accuracy (P_o) was 77.8%, with a Tau coefficient (T_e) of 0.723 ± 0.075. As mentioned previously, a second matrix using the map category proportions could not be computed for percent coral cover.

Only two of the possible coral categories were present in the map (<10% and 10%-<50%), while two points in the accuracy assessment data were classified as 50%-<90%. Accuracy was very high for the softbottom habitats, where a low amount of coral is expected. There was lower accuracy for percent coral on hardbottom habitats. The decision between <10% and 10% - <50% was often difficult to determine, especially where there was a mix of octocorals and scleractinians. Additional ground truthing would improve accuracy of this category.

Table 2.10. Error matrix for percent hardbottom.

Map data (j) \ Accuracy Assessment (i)	0% - <10%	10% - <30%	30% - <50%	50% - <70%	70% - <90%	90% - 100%	$n_{\cdot j}$	User's Accuracy (%)
0% - <10%	**73**			1		2	76	**96.1%**
10% - <30%							0	**n/a**
30% - <50%		1	**1**				2	**50.0%**
50% - <70%							0	**n/a**
70% - <90%	2	1			**16**	10	29	**55.2%**
90% - 100%	1	1	1	3	8	**64**	78	**82.1%**
$n_{i\cdot}$	76	3	2	4	24	76	n=185	
Producer's Accuracy (%)	**96.1%**	**0.0%**	**50.0%**	**0.0%**	**66.7%**	**84.2%**	**P_o =**	**83.2%**
							T_e =	**0.799±0.065**

Table 2.11. Error matrix for percent hardbottom, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category proportions.

Map data (j) \ Accuracy Assessment (i)	0% - <10%	10% - <30%	30% - <50%	50% - <70%	70% - <90%	90% - 100%	$\pi_{\cdot j}$	User's Accuracy (%)	User's CI (±%)
0% - <10%	**0.640**			0.009		0.018	0.666	**96.1%**	**4.5%**
10% - <30%							0.002	**n/a**	**n/a**
30% - <50%		0.002	**0.002**				0.003	**50.0%**	**70.7%**
50% - <70%							0.007	**n/a**	**n/a**
70% - <90%	0.012	0.006			**0.093**	0.058	0.168	**55.2%**	**18.5%**
90% - 100%	0.002	0.002	0.002	0.006	0.016	**0.127**	0.154	**82.1%**	**8.7%**
$p_{i\cdot}$	0.654	0.009	0.004	0.015	0.108	0.202	π=1		
Producer's Accuracy (%)	**97.9%**	**n/a**	**44.0%**	**n/a**	**85.4%**	**62.7%**	**P_o =**	**86.1%**	
Producer's CI (±%)	**2.4%**	**n/a**	**60.1%**	**n/a**	**9.3%**	**12.2%**	**CI(±) =**	**4.5%**	

Table 2.12. Error matrix for percent coral cover.

Map data (j) \ Accuracy Assessment (i)	Softbottom, Coral <10%	Softbottom, Coral 10% - <50%	Hardbottom, Coral <10%	Hardbottom, Coral 10% - <50%	Hardbottom, Coral 50% - <90%	$n_{\cdot j}$	User's Accuracy (%)
Softbottom, Coral <10%	**71**	2	2	1		76	**93.4%**
Softbottom, Coral 10% - <50%						0	**n/a**
Hardbottom, Coral <10%	2	1	**53**	10		66	**80.3%**
Hardbottom, Coral 10% - <50%			21	**20**	2	43	**46.5%**
Hardbottom, Coral 50% - <90%						0	n/a
$n_{i\cdot}$	73	3	76	31	2	n=185	
Producer's Accuracy (%)	**97.3%**	**0.0%**	**69.7%**	**64.5%**	**0.0%**	**P_o =**	**77.8%**
						T_e =	**0.723±0.075**

Conclusions

The results indicate that all levels of map data for Vieques have acceptable accuracy percentages and are suitable for a wide range of scientific and management applications (e.g., Kendall and Eschelbach 2006). Classification errors were primarily between similar habitats such as *Sand* and *Sand with Scattered Coral and Rock* which often lack clear separation when adjacent to each other; *Seagrass* and *Algae* which often occur in mixed beds; and between adjacent categories of percent hardbottom and coral cover. Although the classification schemes are not directly comparable due to region-specific categories, the level of accuracy for detailed structure was similar to that of other recent NOAA benthic habitat maps in St. John, US Virgin Islands (86%, [89% adjusted] Zitello et al. 2009), the Florida Keys

(86% [92% adjusted], Walker and Foster 2009), Palau (90%, Battista et al. 2007b), and the Main Hawaiian Islands (90%, Battista et al. 2007a). Comparisons with other accuracy assessments at the biological cover level are not possible due to the differences in the classification scheme.

For additional details on accuracy assessment methods and computational details see the references in the literature cited section.

2.5 SUMMARY STATISTICS

Of the area considered during the mapping process, 127.4 km² was designated as *Land*. The remaining 357.6 km² were described by 3229 polygons corresponding to the structure and biological cover types of the habitat classification scheme outlined in Section 2.2.

Of these 357.6 km², *Unconsolidated Sediment* and *Coral Reef and Hardbottom* each accounted for 238 km² and 119.6 km², respectively, of Major Structure type (Table 2.13). Together, *Unconsolidated Sediment* and *Coral Reef and Hardbottom* account for 99.99% of Major Structure type; the remaining 0.01% corresponds to *Artificial* structures. The 0.05 km² of *Artificial* type is comprised primarily of Mosquito Pier on the north shore, piers in Esperanza on the south shore, and the sunken U.S.S Killen in Bahia Salina del Sur.

Summary statistics for Detailed Structure highlight the composition of Major Structure types (Table 2.13). Note that Detailed Structure percentages are derived from total mapped area, not within the corresponding Major Structure classification. *Sand* is the most common Detailed Structure type, accounting for 61.6% of the total mapped area (Table 2.13). *Mud* and *Sand with Scattered Coral and Rock* are considerably less common *Unconsolidated Sediment* types, accounting for 2.2% and 2.7% respectively. At 11% of total area, *Pavement* is the second most dominant structure type overall and the

Table 2.13. Area summary of major and detailed geomorphological structure classes in the Vieques benthic habitat map.

MAJOR STRUCTURE	AREA (km²)	PERCENT AREA	DETAILED STRUCTURE	AREA (km²)	PERCENT AREA
Coral Reef and Hardbottom	119.56	33.44	Rock/Boulder	1.38	0.39
			Aggregate Reef	13.79	3.86
			Individual Patch Reef	6.46	1.81
			Aggregated Patch Reef	1.91	0.54
			Spur and Groove	0.02	0.01
			Pavement	39.37	11.01
			Pavement with Sand Channels	5.98	1.67
			Reef Rubble	17.53	4.90
			Rhodoliths	33.11	9.26
Unconsolidated Sediment	237.95	66.55	Sand	220.39	61.64
			Mud	7.88	2.20
			Sand with Scattered Coral and Rock	9.69	2.71
Other Delineations (Land excluded)	0.05	0.01	Artificial	0.05	0.01
Total	357.56	100.00		357.56	100.00

Table 2.14. Area summary of major and detailed cover classes in the Vieques benthic habitat map (excludes land and non-classified artificial areas).

MAJOR COVER	AREA (km²)	PERCENT AREA	PERCENT COVER	AREA (km²)	PERCENT AREA
Algae	156.91	43.88	10% - <50%	5.24	1.47
			50% - <90%	78.96	22.08
			90% - 100%	72.71	20.34
Seagrass	171.28	47.90	10% - <50%	16.92	4.73
			50% - <90%	102.29	28.61
			90% - 100%	52.08	14.56
Live Coral	0	0	10% - <50%	0	0
			50% - <90%	0	0
			90% - 100%	0	0
Mangrove	3.81	1.07	10% - <50%	0.42	0.12
			50% - <90%	0.93	0.26
			90% - 100%	2.46	0.69
No Cover	25.55	7.15	90% - 100%	25.55	7.15
Total	357.56	100.00		357.56	100.00

predominant detailed structure type within *Coral Reef and Hardbottom*. Other common structure types are *Rhodoliths*, which account for 9.3% of total area, and *Aggregate Reef*, which contributes to 3.4% of total area. Although ecologically significant, patch reefs, in the form of *Individual Patch Reefs* and *Aggregated Patch Reefs*, only comprise just over 2% of all the nearshore habitat of Vieques.

Table 2.15. Area summary of percent coral cover for Vieques habitats.

PERCENT CORAL COVER	AREA (km^2)	PERCENT AREA
<10%	333.65	93.31
10% - <50%	23.91	6.69
50% - <90%	0	0
90% - 100%	0	0
N/A	0.004	0.001
Total	357.56	100.00

Seagrass and *Algae* were the dominant biological cover types, accounting for 47.9% and 43.9% of the mapped area, respectively (Table 2.14). *Seagrass* was most common, however it should be noted that beds of submerged vegetation are often a mix of seagrass and algae, and as noted in the previous section, distinguishing between the two in aerial imagery can be difficult. Nearly half of the 43.9 km^2 of algal dominance is covered by a continuous distribution (90% - 100%). This is in large part due to the inclusion of turf algae as a mapped species, since much of Vieques hardbottom is covered by turf in the absence of live coral. Areas with *No Cover* account for 7.2% of the total area. *Mangrove*, a less common dominant cover, constitutes 1.1% of the study area. Although live coral colonies exist throughout the Vieques seascape, no area was mapped that was dominated by *Live Coral*.

Only 23.9 km^2 exhibited a Percent Coral Cover of 10% to <50%. These areas account for 6.7% of the study area, while 93.3%, or 333.7 km^2, have less than 10% coral cover. Furthermore, Coral Cover does not exceed 50% within any single minimum mapping unit of the study area. For this, it is important to remember the influence of minimum mapping units in the habitat mapping process. It is possible that some areas of Vieques are comprised of greater than 50% coral cover, but these areas were not large enough to be mapped with a contiguous minimum mapping unit of 1000 m^2.

The composition and extent of geomorphological structure and biological cover around Vieques varies over space (Figures 2.36-2.38; Kendall and Eschelbach 2006). The area north-northwest of Vieques is dominated by sand with submerged aquatic vegetation, interspersed by numerous patch reefs. Moving east from Isabel Segunda, a system of shallow *Lagoons* and *Reef Flats* extend from shore, bordered seaward by a line of *Pavement* and *Aggregate Reef*. A large area of *Rhodoliths* dominated by algae cover sits offshore in the deeper water. The formation of *Pavement* and *Aggregate Reef* extends around the eastern tip of the island to the south side, where it is more extensive than on the north. Two linear systems of *Pavement* and *Aggregate Reef* are present on the south coast; one close to shore, while another is further offshore along the shelf edge. The large area lying between these two reef systems southeast of Vieques is a depression approaching 30 m in depth that was primarily mapped as *Reef Rubble*. Available ground-truth and accuracy assessment data indicated that the structure constitutes a mix of rubble, pavement and sand. However, the heterogeneity of the structure and depth of this area made distinguishing between the different signatures difficult.

Area designated as *Unknown* exceeds the depth limits (~30 m) for mapping with aerial imagery. NOAA's Biogeography Branch is undertaking a similar effort to develop habitat maps of the deep-shelf area south of Vieques, including the El Seco area to the east. The maps will be derived from acoustic data collected with a multibeam echosounder (MBES).

2.6 COMPARISON TO PREVIOUS NOAA HABITAT MAPS OF VIEQUES

The 2009 mapping effort described in this report marks the second such effort NOAA has conducted to map shallow water marine benthic habitats of Vieques. Components of the new mapping product that mark an improvement over Kendall et al. (2001) include an expanded habitat classification scheme, smaller minimum mapping units, more recent imagery, and improved positional accuracy (Table 2.16). In addition, within the extent area used for this mapping effort, a larger total area was mapped than in the previous mapping effort (~81 km^2). For example, some areas that were mapped as unknown in the previous effort were able to be delineated in the new map due to better remote sensing imagery. These include areas that had been obscured by clouds in the 1999 imagery (e.g., outside the mouth of Puerto Ferro, and southeastern Ensenada Honda) and where image clarity was poor (e.g., the vast rhodolith/algae field northeast of the island).

NOAA's revised approach to mapping nearshore ecosystems has provided significant advantages to better represent the natural environment. As displayed in Table 2.16, the 2009 map was created with finer scale

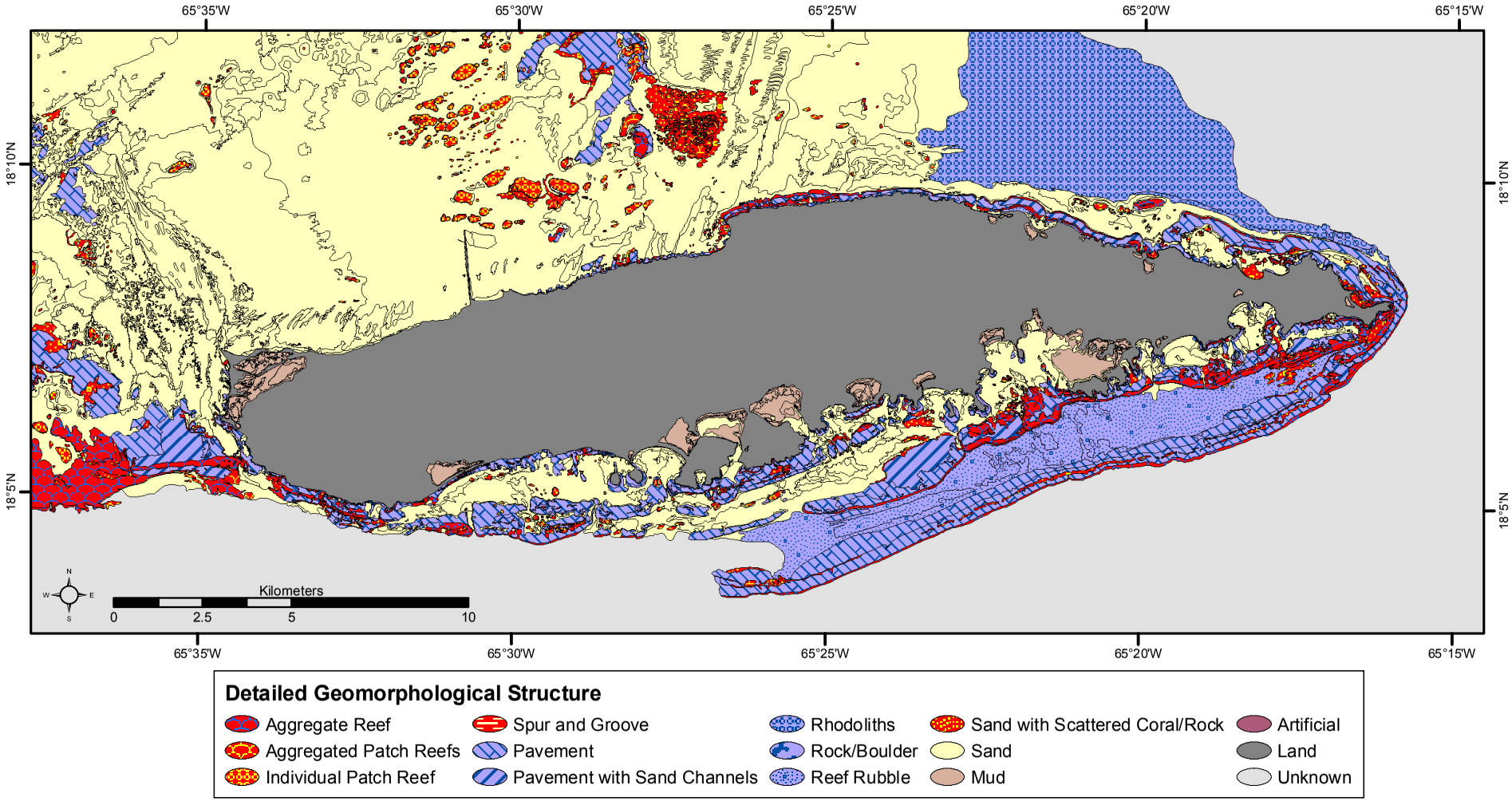


Figure 2.36. Detailed geomorphological structure.

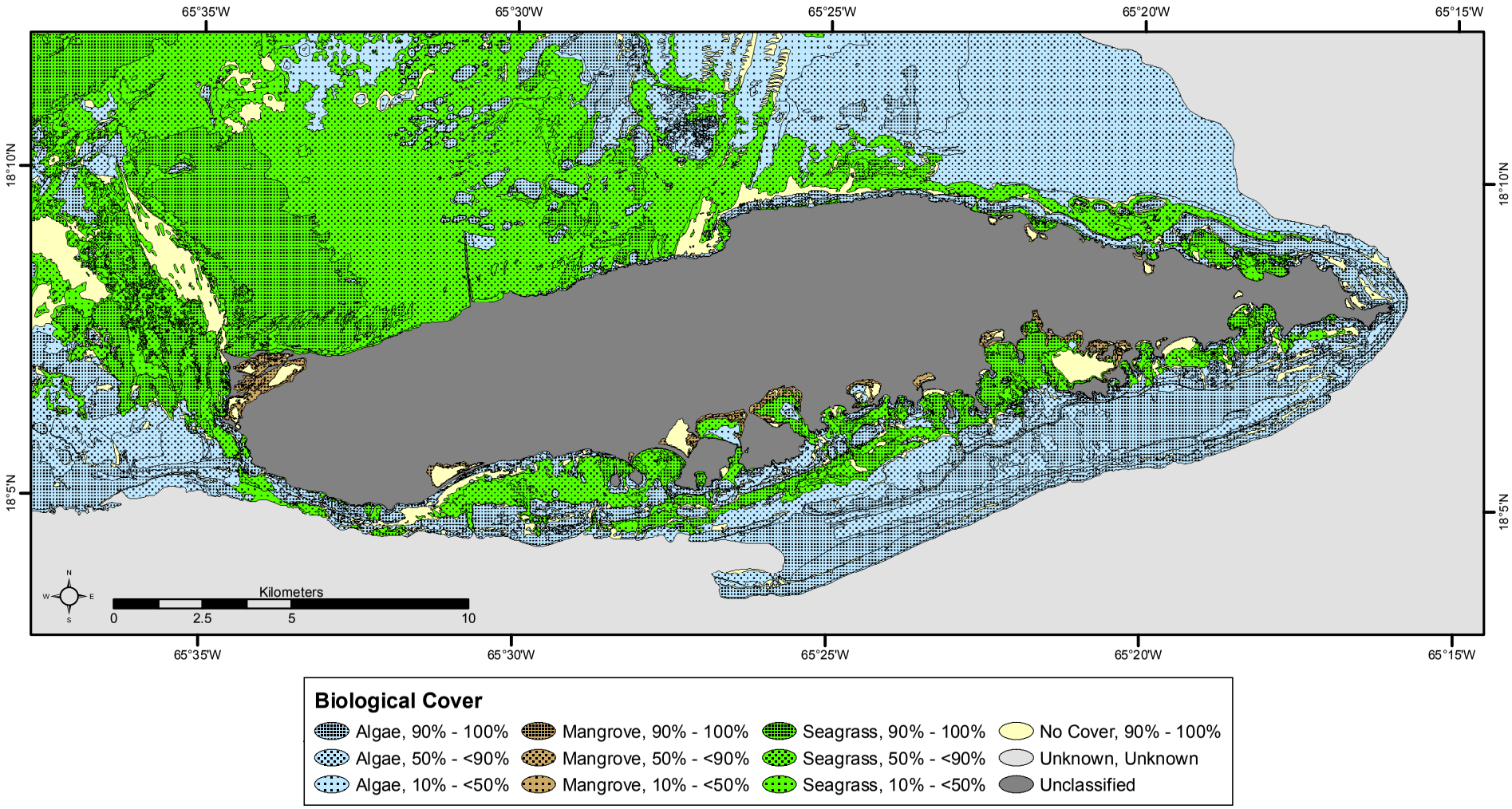


Figure 2.37. Dominant biological cover.

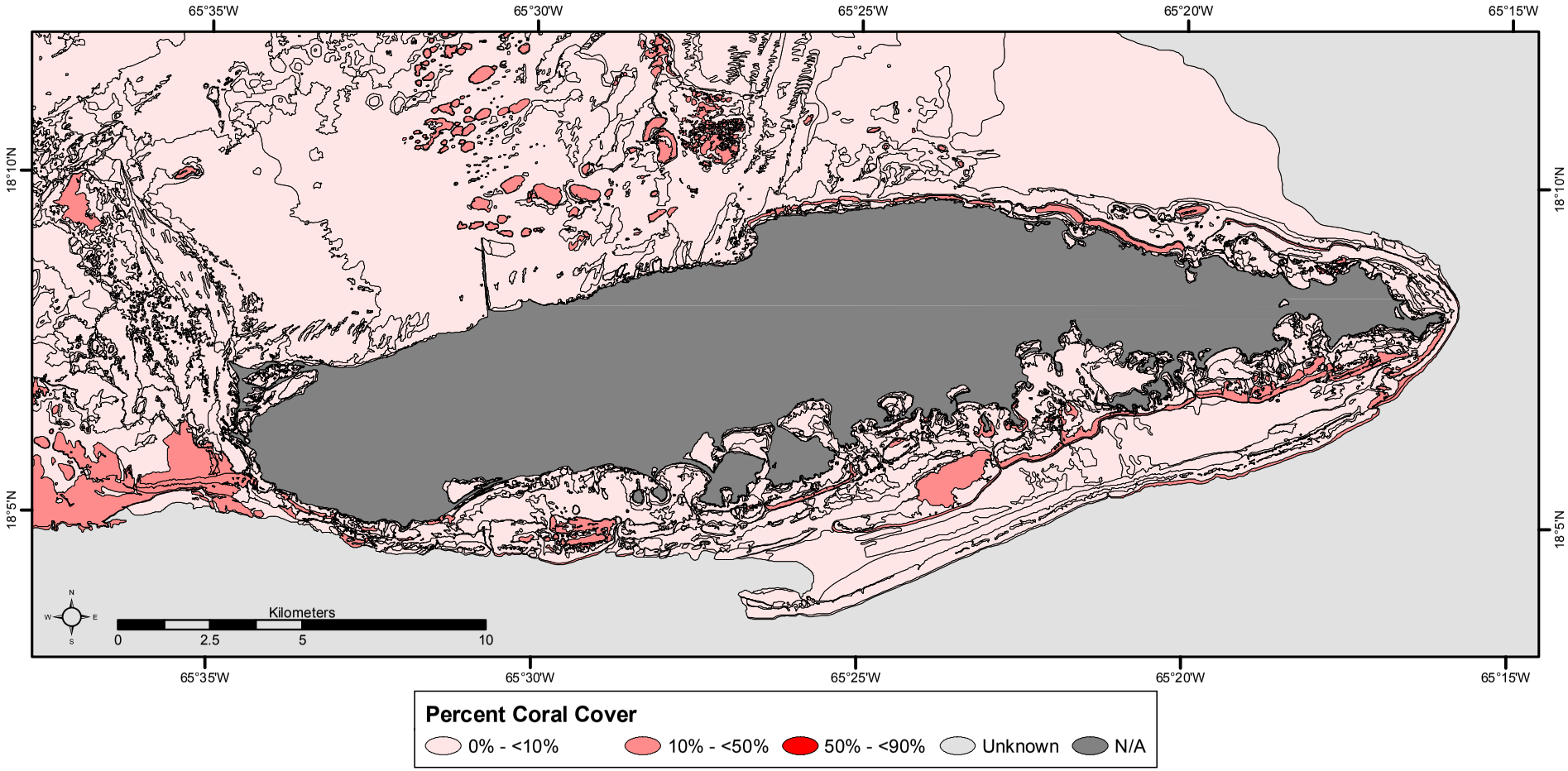


Figure 2.38. Percent coral cover.

mapping standards in both scale of delineation and minimum mapping unit. Following pan-sharpening, the pixel resolution of the IKONOS imagery was 1 m, while the pixel resolution of the 2007 Army Corps orthophotography was 0.3 m. In contrast, the source imagery of the 2001 maps was 2.4 m. The finer scale imagery and reduced scale of delineation resulted in enhanced line accuracy and detail.

Table 2.16. Comparison of basic map characteristics between a previous NOAA effort (2001) and current map of Vieques (2009). Excludes land and unknown areas.

		NOAA MAPPING EFFORT	
		2001	**2009**
MAP	Source Imagery Date	1999	2006-2008
	Scale of Delineation	1:6000	1:4000
	Minimum Mapping Unit (m^2)	4,046	1,000
FEATURE	Number of Polygons	882	3229
	Mean Polygon Area (m^2)	313,930	110,735
	Total Mapped Area (km^2)	276.57	357.56
	Sum of Polygon Edges (km)	2983	5544
	Mean Polygon Length (km)	3.39	1.72

A four-fold reduction in the MMU from an acre (4,046 m^2) to 1000 m^2 in the 2009 mapping effort had a large impact on the final content of the mapping product. The smaller minimum mapping unit results in ~3.5 times as many polygons and about three times as small mean polygon area. The reduced MMU allowed for a more accurate depiction of patchy environments. For example, in the previous mapping effort, most of the patch reefs north of the island were below the MMU and thus grouped together into polygons of aggregated patch reefs. As illustrated by Figure 2.39, many of these patch reefs could often be individually drawn in the new map. In total, 609 individual patch reefs were mapped in the 2009 map, compared to 88 within the same extent in 2001. Although other factors may have contributed to this difference (e.g., image quality), the ability to delineate more features due to the reduced scale and MMU is likely the primary reason.

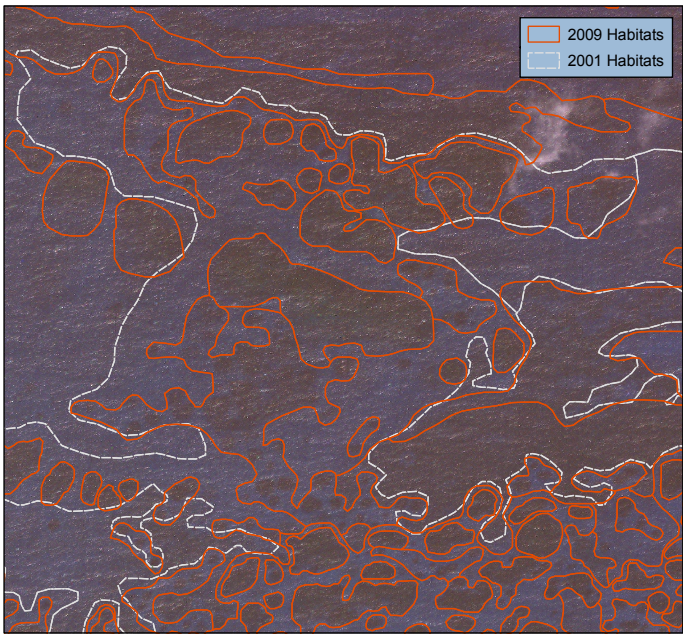


Figure 2.39. Comparison of 2001 and 2009 NOAA benthic habitat boundaries to illustrate the difference in the minimum mapping unit on delineation of patch reefs north of Vieques.

Periodic re-mapping of an area can serve as an important monitoring tool. Although the different classification schemes and MMUs prohibit a quantitative comparison between the 2001 and 2009 maps, there appear to be some changes in biological cover on softbottom between the two time periods. The Escollo de Arenas, extending from the northwest tip of the island, is a dynamic feature whose shape and shifting sands are influenced by longshore and tidal currents (Rodriguez and Trias 1989). Large storm events can transport large volumes of sediment into adjacent seagrass beds (e.g., Hurricane Hugo, Rodriguez et al. 1994). Areas south/west of the sand wedge have experienced a regrowth of seagrass between 1999 and 2007, when the previous and newer imagery was taken, respectively (Figure 2.40). In addition, the eastern edge of Escollo de Arenas has been filled in by vegetation. One of the new satellite images captured the strong currents and sediment transport that can occur in this area (Figure 2.40). The high turbidity in the water column obscured the bottom on much of the north side of the island on this day. Tidal inflow of a sediment plume into Laguna Kiani, a mangrove lagoon on the northwest tip, was also visible. Further seagrass re-growth is apparent along the southeast coast of Vieques, including Bahia Salina del Sur.

2.7 PROJECT DELIVERABLES

A suite of products associated with the Vieques benthic habitat map are available to the public on a NOAA Biogeography Branch website devoted to this mapping effort (http://ccma.nos.noaa.gov/ecosystems/coralreef/vieques.html). The project deliverables include:

• Benthic habitat maps in GIS format,

• Remotely sensed imagery, including satellite and airborne imagery,

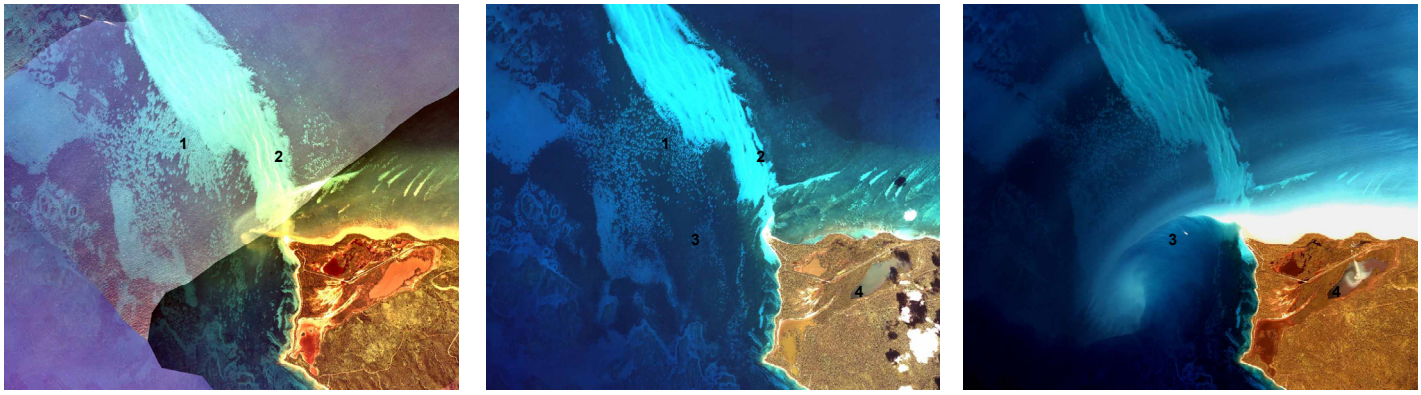


Figure 2.40. Comparison of seagrass coverage near the Escollo de Arenas in the 1999 (left) and 2007 (middle) imagery. Example areas of seagrass growth east and west of the sand wedge are labeled 1 and 2. Another recent IKONOS image (right panel) was captured on a day of strong currents and high turbidity (labels 3 and 4).

• Underwater video of ground validation and accuracy assessment field sites, including GIS files of their locations,

• Classification manual (contained in this report),

• Description of the specific methods used to create the habitat maps (contained in this report),

• Assessment of the thematic accuracy of the maps (contained in this report),

• FGDC-compliant metadata for all GIS products, and

• An interactive, web-based map that allows users to query and display all spatial datasets and underwater video.

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