

Atlas of Shallow-Water Benthic Habitats of Coastal Texas:

Espiritu Santo Bay to Lower Laguna Madre, 2004 and 2007

December 17, 2009

National Oceanic and Atmospheric Administration (NOAA)
Coastal Services Center
Texas Parks and Wildlife Department
Texas A&M University–Corpus Christi
Fugro EarthData



Atlas of Shallow-Water Benthic Habitats of Coastal Texas: Espiritu Santo Bay to Lower Laguna Madre, 2004 and 2007

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December 2009

Disclaimers

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Citation

This publication should be cited as follows:

Finkbeiner, M., J. D. Simons, C. Robinson, J. Wood, A. Summers, and C. Lopez. 2009. *Atlas of Shallow-Water Benthic Habitats of Coastal Texas: Espiritu Santo Bay to Lower Laguna Madre, 2004 and 2007*. NOAA Coastal Services Center, Charleston, SC.

Acknowledgments

This work was funded by NOAA grant number NA05NOS4730008 to the Harte Research Institute at Texas A&M University–Corpus Christi. In addition, NOAA awarded a contract to the team of Fugro EarthData, Alta Vista Company (now Kass Green and Associates), and Avineon, Inc. (Contract number EA133C-05-CQ-1051).

In-kind services were provided by the Texas Parks and Wildlife Department and the Texas General Land Office. We thank Holly Bellringer and Jenny Wrast for assistance in the ground-truthing operation and Norman Boyd for his assistance in planning and weather observations for the San Antonio Bay overflight.

A number of individuals were essential to the success of this effort. The authors would like to recognize the contributions of Bill Stevenson, Kass Green, Keith Patterson, Joseph Muller, and Dan Bubser.

Dedication

The authors wish to dedicate this publication to the memory of Dennis Pridgen of the Texas Parks and Wildlife Department. Dennis was a key figure in the initial design phase and also provided invaluable field experience at many stages of the project. His knowledge, collaboration, wisdom, and tireless support of this effort are greatly appreciated and missed.

Related Websites

The spatial habitat data represented in this document can be downloaded for use in a geographic information system at:

www.csc.noaa.gov/digitalcoast/data/benthiccover/download.html.

The Texas Parks and Wildlife website has statewide seagrass maps at:

<http://gis-apps.tpwd.state.tx.us/website/Seagrass>.

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INTRODUCTION

The benthic habitats of the Texas coast are some of the most productive in the world and serve as important habitat for estuarine-resident and -dependent organisms. These habitats include **seagrass meadows**, which predominantly occur in the mid and southern reaches of the Texas coast; **oyster reefs**, which tend to occur primarily in the northern and central sections of the Texas coast; **intertidal marshes** dominated by *Spartina alterniflora*, which occur in all sections of the Texas coast, although to a greater extent in the northern areas of the coast; and **black mangroves** (*Avicennia germinans*), which occur primarily in the southern reaches but have spread much farther north in the past 10 to 20 years.

The seagrass resources of the state of Texas have never been synoptically mapped at a regional scale to assess status and trends. The Texas Coastal Bend (Aransas and Corpus Christi Bay systems and the Upper Laguna Madre) seagrasses were mapped in the early 1990s (Pulich and others 1997) using 1:24,000-scale aerial photography. Pulich and others (1997) also included an analysis and mapping of seagrasses from historical aerial photography from the 1950s and the 1970s at selected areas in the Coastal Bend. Recently the state adopted a Seagrass Monitoring Plan (Pulich and others 2003) that explicitly calls for the state to perform a regional mapping of its seagrass resources at a scale of 1:24,000 on a five-year schedule. In addition, seagrasses have been added as an “aquatic life use” by the Texas Commission on Environmental Quality as part of its surface water quality monitoring program (TCEQ 2008).

The oyster resources of the state of Texas are in need of an updated mapping effort. The oyster reefs of Galveston Bay were mapped by ground survey (Benefield 1976) and by the use of subbottom profiler (Powell and others 1995). The subtidal oyster reefs of Lavaca Bay were mapped using side-scan sonar and subbottom profiler technologies (Simons and others 2004). The subtidal oyster reefs of Copano Bay have recently been mapped by acoustic survey techniques, with publication of maps due by the end of 2009. Aerial imagery analysis from this study has been used to augment the acoustic mapping effort in Copano Bay. Mapping of the subtidal oyster reefs in Sabine Lake and Galveston Bay is currently underway, while there are tentative plans for similar acoustic surveys in San Antonio, Aransas, and Nueces Bays. Since

acoustic methods are only appropriate in waters 2.5 feet and deeper, the aerial survey methods detailed in this report are excellent for mapping shallow fringing and emergent reefs.

This volume presents a series of digital color aerial images overlaid by interpretive maps of the benthic habitats of the middle and lower coastal bays and estuaries of Texas. The bays included in this atlas are San Antonio Bay, Espiritu Santo Bay, Copano Bay (including Mission, St. Charles, and Port Bays), Aransas Bay (including Ayers and Mesquite Bays), Redfish Bay, Nueces Bay, Corpus Christi Bay, Upper Laguna Madre, Baffin Bay (including Alazan, Cayo del Grullo, and Laguna Salada Bays), and Lower Laguna Madre (including South Bay). Figure 1 shows the extent of each bay system and the area covered by each section of map sheets in the document.

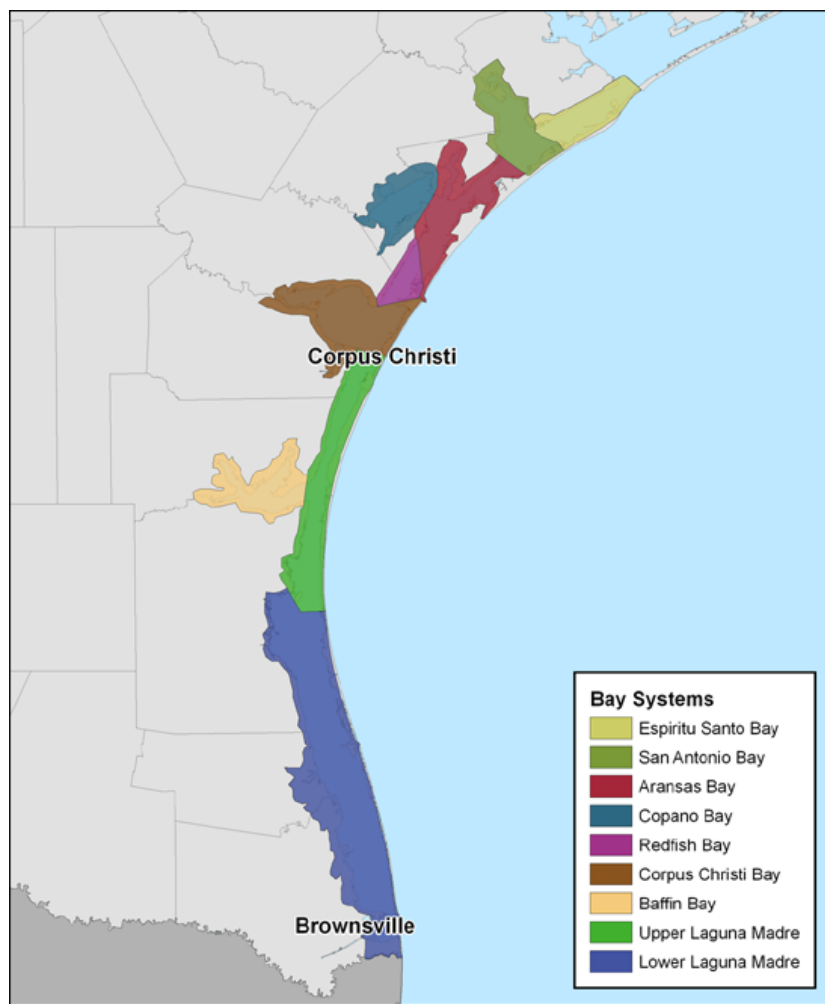


Figure 1. Study area locations and mapping units.

The source imagery for this mapping effort was 1-meter resolution digital multispectral imagery, and the interpretive maps were created using semi-automated image processing and extensive field validation (Green and Lopez 2007). These are discussed in greater detail in the image segmentation section. The imagery and maps included in this report will be a valuable resource for managing and preserving seagrass and other coastal benthic habitats by providing either baseline or change detection data. While this publication is intended for state and federal resource agencies, private citizens and other entities are likely to find it useful. The data presented here can be used to establish trends in distribution and abundance of shallow-water benthic habitat, identify essential fish habitat and harvest areas, aid in permitting and the permit review process, and locate possible restoration areas. Citizens will also be able to use maps to locate new fishing grounds or learn more about ones they already fish.

IMAGE ACQUISITION AND MAPPING PARAMETERS

The following sections describe the specifications used to develop the benthic habitat data for coastal Texas from Espiritu Santo Bay to the Mexican border. Selection of appropriate mapping specifications is critical for ensuring that the resulting data are useful for their intended purpose and are a strong driver of project costs. The specifications in this project build on similar projects conducted by the National Oceanic and Atmospheric Administration (NOAA) elsewhere in the continental United States and have been applied in a variety of environmental settings.

Classification System

Selection of the appropriate classification system for any mapping project is essential for capturing useful information about the environment. Ideally, the classification system should serve the needs of local users as well as those interested in regional or national trends. It should also be amenable to the technologies used to gather and apply the data.

Hierarchical systems are especially useful for studies relying on remotely sensed data, since they allow the analyst to identify habitat units to the level of detail supported by the technology, and permit aggregation upward to more general units when necessary. This minimizes potential data gaps in the final map product.

For the Texas project, the Florida System for Classification of Habitats in Estuarine and Marine Environments (SCHEME) was used (Madley and others 2002). Although this system was developed for application in Florida's intertidal and shallow subtidal environments, the habitat classes, or units, occur almost universally in continental U.S. waters, and the system translates well to the Texas gulf coast. SCHEME is a hierarchical system that also contains modifiers that allow further description of habitat units. It was also developed with aerial photography as the expected data source, although it can be applied using other source data. All these factors and its successful use in previous NOAA mapping and field studies made SCHEME a logical choice for the Texas coast.

The SCHEME system

SCHEME is organized into four hierarchical levels beginning with “class” at the uppermost level. Below “class” are four fully nested “subclass” levels. SCHEME was designed for landscape-level mapping and is expected to be applicable at the class level at image scales of 1:48,000 and higher. Subclass level distinctions usually require ground information.

Mapping decision-rule guidance accompanies the SCHEME classification structure. These rules formed the basis for the semi-automated mapping methods covered in the “Benthic Habitat Data Development” section. For this project, the intent was to map any and all of the SCHEME habitats encountered down to the subclass 2 level and, if possible, to the subclass 3 level. In practice, only a subset of the classes or subclasses was present in the project area to map.

The class units are generally equivalent to the Cowardin and others (1979) classes and are intended to facilitate cross-walking between the two systems. Like Cowardin, SCHEME classes contain both substrate and biological cover elements. Unlike Cowardin, tidal regime and salinity are not upper-level discriminators for SCHEME, since they would potentially restrict the use of the system for landscape-level mapping. Rather, these environmental parameters are handled as modifiers when data support their use.

The subclass categories (1-4) further define the mix of biotic and physical class units. Parameters captured in the subclasses include sediment character, vegetation type, reef structure, biological groups, and landforms.

The modifiers available within SCHEME fall into either general modifiers or taxonomic modifiers. General modifiers include more information on biologic groups, anthropogenic structures, impacts and injuries, drift material, and sediment chemistry. Taxonomic modifiers allow the user to record the presence of specific species presence within a mapped unit. Table 1 illustrates the SCHEME habitat classes, including those encountered in coastal Texas.

Table 1. Benthic habitat classes used on the coast of Texas from the Florida System for Classification of Habitats in Estuarine and Marine Environments (SCHEME). (See Madley and others 2002 for a listing of the complete classification.)

Class	Subclass 1	Subclass 2	Subclass 3	Subclass 4
Unconsolidated Sediments	Mud			
Submersed Aquatic Vegetation (SAV)	Submersed Rooted Vascular Plants (SRV)	Continuous SRV	Dense Patches of SRV in a Matrix of Continuous, Sparse SRV	
		Discontinuous SRV		
	Macroalgae	Attached Macroalgae	Continuous Attached Macroalgae	
	Mollusk Reefs	Bivalve Reefs		
	Annelid Reefs			
Tidal Marsh	Salt Pan			
Tidal Swamp				
Land				
Unknown Benthic Habitat	Turbidity Plume			

In addition to the habitat units within SCHEME, the general modifier *Mat Algae* was used in many areas, especially in the shallow intertidal regions of Lower Laguna Madre. No other modifiers were used in the project.

Some of the habitat units not captured in the mapping did not occur within the project area, such as the coral reef classes. In other cases, the sensing technology, scale of the imagery, and minimum mapping unit were insufficient to identify units. This was normally the case in the lower subclass levels.

Minimum Mapping Unit

The minimum mapping unit (MMU) reflects the smallest feature or spatial extent to be captured as an individual element in the map. Objects or areas smaller than the MMU are aggregated into larger spatial units or, in the case of the Texas coastal data, polygons. The MMU for the coastal Texas project was 100 square meters, that is, an area 10 meters by 10 meters on the ground. This is a relatively small MMU for landscape level mapping of this type, and the result is a map with high levels of detail. This MMU was chosen to capture small features such as oyster reefs and to form the basis for future change detection efforts.

The MMU for this project was agreed upon by the Texas Parks and Wildlife Department, NOAA, the Harte Research Institute, and other project partners and had been successfully applied in earlier NOAA projects.

Interpretation Rules

In nature, habitat boundaries usually occur across gradual transition zones (ecotones). It is not uncommon for multiple habitat units to occur together or in very close spatial proximity. These mixed areas require rules for assigning the area to a habitat unit in the map. Most projects develop interpretation rules based on the primary intended use of the resulting map product. In the coastal Texas project, the primary project goal was to capture seagrass meadows with high precision and accuracy to support change detection and trend analysis. The interpretation rules for this project were built on rules long used by the St. Johns River and South Florida Water Management Districts for their ongoing seagrass monitoring efforts in eastern Florida. Since the deepwater edge of seagrass reflects overall water clarity and seagrass often expands or retreats spatially based on either favorable or unfavorable conditions, the rules applied on the Texas coast are focused on habitat edges.

The following rules were used to guide the mapping effort. These rules were incorporated into the semi-automated methods to be described later in this document.

- A. Outer boundaries of habitats are of equal importance to the internal structure, patchiness, shapes of sand patches, etc. within habitats.

- B. It is more important to include small isolated habitat patches than similarly sized patches that are part of a larger matrix.
- C. In cases where an area may have continuous or discontinuous SRV [submersed rooted vasculars] (seagrass) cover with macroalgae accumulations in the grass canopy, the polygon shall be assigned to the appropriate SRV seagrass class and a modifier used to document the presence of macroalgae.
- D. In cases where an area may have multiple small habitat components, then the polygon label shall reflect the majority habitat within the area.
- E. Areas that are un-interpretable because of depth shall be assigned to the “Unknown Benthic Habitat” class.
- F. In tidal flat areas where ephemeral algal mats may develop during periodic submersion, the areas shall be labeled based on sediment character and the Mat Algae modifier added.

Benthic Habitat Units in the Coastal Texas Project Area

The following section describes the SCHEME habitat units that were encountered on the Texas coast and captured in the benthic habitat data sets. The definitions are drawn directly from the SCHEME document. The rationale behind including them in the maps is also explained in these sections.

Unconsolidated Sediments

“The subclasses within the unconsolidated sediments class were modeled after the commonly used Wentworth size classes (Locker 1999). Particle size fractionation classification is desirable for research related to benthic infauna, sediment movement, and artificial reef placement. These category distinctions are most accurately made with sieve tests, although Subclasses (i.e., mud vs. sand vs. pebble) distinctions are commonly estimated using observer sight and touch during field visits.” (Madley and others 2002)

Substrates with less than 10% colonization by submerged aquatic vegetation (SAV) or corals are categorized as “Unconsolidated Sediments.” Unconsolidated sediments were of interest in this project since they are areas of potential SAV colonization. Those areas visible on the aerial

imagery lie within the photic depth and are thus available for new SAV, or they may illustrate areas where SAV has been lost (and are now unvegetated), but which are still photic. It should be noted that the source imagery was acquired under very low water levels and under normal conditions these areas would be deeper.

The following photos (Figures 2, 3 and 4) illustrate types of unconsolidated sediment observed in the project area. Figure 2 shows an area of unconsolidated sediment high in the intertidal zone. Infrequent inundation and high evaporation rates result in a crust of accumulated salts.



Figure 2. Unconsolidated sediment-mud-salt flat. Southern Upper Laguna Madre.



Figure 3. Unconsolidated sediment-mud. Northern Lower Laguna Madre.



Figure 4. Unconsolidated sediment-mud. Note grey color and remnant *Halodule wrightii* blades. Northern Laguna Madre.

Submerged Aquatic Vegetation (SAV)

“Any combination of SAV (i.e., seagrasses, oligohaline grasses, attached macroalgae, and drift macroalgae) that covers 10-100% of the substrate. If reef or hardbottom is more abundant than the SAV, then the polygon should be recorded as *Reef/Hardbottom* and SRV should be noted with modifiers.” (Madley and others 2002)

Within the SCHEME “SAV” class are the two major types of SAV, rooted vascular plants and macroalgae. In this project the mapping guidelines required that vascular plants be distinguished from nonvascular algae. In most cases this was achievable; however, in at least one instance, the delineation had to be aggregated upward to the more general SAV class.

Submersed Rooted Vascular (SRV) Plants – This unit consists of areas with more than 10% bottom cover by SRV. In coastal Texas this is normally one of the true marine seagrass species or widgeon grass (*Ruppia maritima*). Within this subclass are further subdivisions based on percent cover of the bottom.

Continuous SRV – Areas with between 75 and 100% seagrass coverage of the substrate (Figures 5, 6, 7, 8, and 9).

Patchy SRV – Areas with between 10 and 75% bottom coverage by vascular plants (seagrasses) (Figure 10).



Figure 5. Continuous SRV. Northern Laguna Madre.



Figure 6. Continuous SRV, *Halodule wrightii*. Redfish Bay.



Figure 7. Continuous SRV, *Thalassia testudinum*. Redfish Bay.



Figure 8. Continuous SRV, *Halodule wrightii*, drift algae. Lower Laguna Madre.



Figure 9. Continuous SRV, *Halodule wrightii*. Lower Laguna Madre.

Macroalgae – As with the vascular plants, the threshold for this unit is >10% cover by macroalgae. This can consist of either monotypic stands or mixed beds of algae.

Attached Macroalgae – These algae are secured to the substrate via holdfasts, rhizomes, or other structures.

Continuous attached macroalgae – As with the vascular plants, this category includes areas with between 75 and 100% bottom coverage.

Discontinuous attached macroalgae – Areas of attached macroalgae with breaks in cover that result in isolated patches, usually in unconsolidated bottom but can occur elsewhere.



Figure 10. Patchy SRV, with some attached macroalgae. Lower Laguna Madre.

Drift Macroalgae – Habitat with 10% or more cover of mixed or monospecific algae that is not attached to the substrate. Drift algae moves or accumulates based on wind or wave forces. It may be ephemeral or persistent within an area because of lack of energy or entanglement on substrate features (Figures 10 and 11).

Continuous drift macroalgae – These are areas with more than 75% bottom coverage by drift algae.

Discontinuous drift algae – Areas with between 10 and 74% drift algae. Isolated patches of unconsolidated or hard bottom will occur within this subclass



Figure 11. Drift algae over continuous SRV. Redfish Bay.



Figure 12. Drift algae in canopy of continuous SRV. Redfish Bay.



Figure 13. Submerged aquatic vegetation. Mix of attached macroalgae (left) and sparse but continuous SRV (right). Espiritu Santo Bay.



Figure 14. Unconsolidated sediments, mat algae. Lower Laguna Madre.



Figure 15. Unconsolidated sediments, mat algae. Lower Laguna Madre.

Reef/Hardbottom

Hardened substrate of unspecified relief formed by the deposition of calcium carbonate by reef building corals and other organisms or exposed bedrock, possibly with various degrees of concealment from attached plant and animal colonization. Unconsolidated bottom and SAV may occur within these habitats, although in less abundance than the reef/hardbottom.

Within the “Reef/Hardbottom” class are four subclasses at level 1 (Coral Reef, Mollusk Reef, Annelid Reef, and Hardbottom). No coral reef or hardbottom subclasses were present within the Texas project area. The following sections describe the Mollusk and Annelid Reefs which were present and mapped.

Mollusk Reef – Concentrations of sessile mollusks that attach to hard substrate and with the correct conditions will proliferate, allowing the reef to grow.

Bivalve Reef – Both oyster and mussel reefs would fall into this subclass. On the Texas coast, both fully articulated oyster reefs and areas of semi-consolidated shell bottom were mapped. These shell bottom areas often surrounded the

cohesive reef structure and occasionally covered extensive reaches of the bottom (Figure 16).



Figure 16. Bivalve reef. Mansfield Pass area, Northern Lower Laguna Madre.

Gastropod Reef – No gastropod reefs were observed in the Texas project area.

Annelid Reef – In the SCHEME system, this subclass refers primarily to sabellariid worms; however, on the Texas coast it was normally serpulid worms that formed reef structures. These often took the form of large boulder-shaped formations (Figures 17 and 18).



Figure 17. Annelid reef. Northern Laguna Madre.



Figure 18. Transition between SAV and unconsolidated sediments; worm tubes. Northern Lower Laguna Madre.

Tidal Marsh

Communities of emerged halophytic vegetation along low wave energy intertidal areas and river mouths. This class is equivalent to the estuarine emergent class within the Cowardin classification. Although many areas of the Texas coast only experience minor tidal fluctuation, the dominant vegetation is equivalent. Smooth cordgrass, glasswort, saltwort, etc. were commonly found in these areas (Figures 19 and 20).



Figure 19. Tidal marsh. Arroyo Grande area, Northern Lower Laguna Madre.



Figure 20. Tidal marsh. Espiritu Santo Bay.

Tidal Swamp

Dense, low forests primarily located along coastal areas (Figures 21 and 22). Various tidal marsh grasses and shrubs may be associated, but these communities are dominated by a mix of red, black, and white mangroves. On the Texas coast, this class almost universally consisted of shrubby black mangroves (*Avicennia germinans*) with *Spartina* or other emergent vegetation occasionally interspersed in small areas. This normally occurred at the high range of tidal inundation. Small open water areas were also present within the mangrove thickets. Those ponds that were larger than the minimum mapping unit (100 square meters) were delineated separately.



Figure 21. Tidal swamp. Espiritu Santo Bay.



Figure 22. Tidal swamp. Espiritu Santo Bay.

Land – Unclassified

Areas above the perceived high-tide line were assigned to this class. In addition, water areas outside the mapping boundary (i.e., freshwater ponds with no connectivity to the main bays) were also included. This delineation was usually made based on image signature and vegetation and soil conditions during field visits.

In the Lower Laguna Madre, extensive intertidal flats occasionally experience longer periods of submersion. During field visits these were often dry but had a remnant presence of mat algae or dead seagrass, thus these areas were assigned to the unconsolidated sediments class.

Modifiers

Only a few modifiers were used in the project. The most common modifier was “mat algae” for unconsolidated bottom classes (Figure 23). Occasionally, the drift macroalgae class was used to note algal accumulations, either on the bottom or within the seagrass canopy. “Wrack” (Figure 24) and “shell hash” (Figure 25) modifiers were also used.



Figure 23. Unconsolidated sediment, drift algae. Espiritu Santo Bay.



Figure 24. Wrack. Lower Laguna Madre.



Figure 25. Unconsolidated sediments – shell.

Taxonomic Modifiers

The only taxonomic modifier used was the *Avicennia germinans* unit (black mangrove) to further describe the Tidal Swamp class. Areas mapped as Tidal Swamp consisted almost exclusively of this species.

Field signature development and validation of the map data confirmed that the SCHEME system allowed reliable delineation of the habitat units in the project area and that no habitats were missed because they were not present in the system.

Source Data Information

Successful benthic mapping using aerial optical sensors requires adherence to several environmental and mission restrictions. These requirements (1) maximize the opportunity for the penetration of light and thus the ability to detect features at the maximum possible depths, and (2) reduce the amount of water between the sensor and the benthos. The parameters applied in the Texas project follow protocols developed and successfully applied at many other locations along continental U.S. coasts. Below are the general recommendations for capturing optical imagery suitable for benthic mapping.

The following environmental parameters are normally required for planning and acquiring benthic mapping imagery and were the requirements for the Texas project.

Environmental Parameters

- | | |
|-------------|---|
| Tidal Stage | Imagery should be acquired within two hours of the lowest tide. Negative low tides are preferred. |
| Wind Speed | No wind is optimal; however, low wind speeds (below 10 mph) are acceptable. |
| Sea State | Imagery is to be acquired during calm surface water conditions to avoid breaking waves and foam that obscure bottom features. |
| Turbidity | Imagery must be acquired when turbidity is low, not immediately following heavy rains or persistent strong winds. Local project partners serve as the source of information for this determination. |

Sun Angle	Sun angles above 30° are optimal. Sun angles above 40° are unacceptable because of reflected sunlight returning back to the sensor (although this is a function of each sensor system).
Phenology	Fall imagery, acquired during annual low-tide periods but while seagrass biomass is still present, is preferred.

In addition, a number of image parameters are important to a successful mapping effort. These parameters are typically driven by cost, project area characteristics, the purpose of the mapping, and the methods to be used in developing the habitat data. The specifications below have been used successfully by NOAA and others and were the requirements for the Texas project.

Imagery Specifications

- The horizontal spatial accuracy of the imagery shall be within +/- 5m CE95 of position on the ground. The contractor shall provide documentation to the government showing how this specification was met.
- The radiometric resolution of both the CIR (color infrared) and RGB (red, green, blue) image composites shall be 8-bit.
- The imagery shall be processed to remove atmospheric effects such as haze and to highlight the spectral response of submerged areas.
- The imagery shall have a minimal exposure variation between adjacent flight lines.
- Both the CIR and RGB image sets shall be tiled according to the existing U.S. Geological Survey digital ortho quarter quad boundaries. A small buffer (~100 meters) shall be produced with each tile to prevent gaps in coverage.
- The spatial resolution (pixel size) of the imagery shall be 1 meter x 1 meter.
- The imagery shall be delivered in a Universal Transverse Mercator – Zone 14 projection using the North American Datum of 1983 (NAD83).
- Any band offsets within either the CIR or RGB composites shall not exceed 1 pixel.
- The imagery shall be delivered in GeoTiff format to facilitate analysis in a variety of software environments.

The Texas mapping project relied primarily on airborne multi-spectral imagery obtained from two different sensors acquired at different times. Early in the project, recently acquired National Agriculture Imagery Program (NAIP) imagery was evaluated for suitability for benthic mapping. The NAIP data are normally collected without consideration of the environmental requirements needed for benthic mapping; however, the 2004 NAIP missions over the Texas coast from Ayers Bay south took place under ideal conditions for imaging submerged habitats.

To comply with the project imagery specifications, the NAIP imagery was reprocessed to create the 4-band (red, blue, green, near-infrared) data set and to meet the spatial accuracy requirements. This reprocessed imagery was used for mapping the Aransas Bay, Copano Bay, Redfish Bay, Corpus Christi Bay, Nueces Bay, Baffin Bay, and Upper and Lower Laguna Madre systems.

Turbidity was too high in San Antonio and Espiritu Santo Bays at the time of the NAIP overflight to use those data for benthic mapping. A separate mission was planned to acquire imagery of those bay systems. The mission took place under the above environmental and image requirements and was accomplished in December 2007. This was advantageous because it again took place during the annual low-tide period on the Texas coast and at a similar seasonality as the NAIP data.

The two image sets were collected with different sensors. The NAIP data were collected using the Leica ADS-40 digital sensor, and the 2007 mission was collected using the UltraCam sensor. These sensors are both 4-band multi-spectral imagers, but the ADS-40 system relies on a line scanning technology while the UltraCam employs a more traditional frame camera method for obtaining the data. The resulting final data sets have some differences in appearance, but the automated methods used for the mapping were successful on both image sets with only minor adjustment.

To develop workable image products to support the semi-automated mapping, the imagery was mosaiced and re-tiled according to the digital ortho quarter quad grid and resampled to a 2-meter pixel.

BENTHIC HABITAT DATA DEVELOPMENT

Benthic habitat or cover maps have long relied on manual interpretation as the primary method of data development. Spectral information from submerged features is often limited, and the appearance of any given cover type is often highly variable because of water conditions or depth, and spatial context. Shape and pattern are also key characteristics that allow discrimination of different habitats.

All these issues limit the use of many common image classification algorithms. However, recent advances in object oriented image classification methods and incorporation of ancillary data into the automated mapping processes have allowed these tools to be useful for landscape-scale inventorying and mapping. These tools take shape, size, and spatial relationships into consideration and have demonstrated effectiveness in capturing a significant portion of the habitats present on the Texas coast. Inevitably, however, there are areas where the accuracy of these semi-automated methods diminishes, and a manual interpretation process is needed to complete the mapping. Automated, object-oriented processing followed by manual interpretation was used in developing the coastal Texas data sets.

The mapping process for the Texas project can be broken into three components: signature development, image analysis, and internal assessment. The following sections describe these process components in more detail.

Signature Development

Signature development is the process by which variation in the source data (imagery) is correlated with habitat types on the ground. This information “calibrates” the subsequent mapping effort and is used to train the analyst doing the mapping, serving as an input to any automated routines used. Signature development is critical to addressing variability in water, illumination, and habitat condition. Samples are chosen to identify representative examples of the habitats present in the area, identify areas of uncertainty, and to confirm assumptions in areas where the habitat seems obvious.

The Fugro EarthData team conducted three signature development trips for Phase I of the project (Ayers Bay south to Upper Laguna Madre), totaling 19 days over a two-month period from May 22 to July 20 2006:

- May 22 -26,
- June 5 -16, and
- July 17 20

Separate trips were conducted for Phase II of the project area (Lower Laguna Madre and San Antonio/Espiritu Santo Bays). This was a function of the logistics required for each trip and the time when newly acquired or reprocessed source imagery became available. Dates of these trips were as follows:

Lower Laguna Madre, 2007

- July 9-12, and
- August 27-29

San Antonio/Espiritu Santo Bays, 2008

- May 13-15

Two types of information were collected during the trips:

1. Qualitative notes and remarks concerning local knowledge about the causes of variation in the project area's benthic habitat. All trips were supported and attended by NOAA, Texas Parks and Wildlife, or Texas A&M Corpus Christi personnel, whose contributions of expertise and resources were critical to the success of the project.
2. Quantitative data about specific example sites within the project area. Field sample sites were chosen to adequately capture (1) all the habitat classes of the classification scheme and (2) all types of spectral variation in the imagery. A random number generator was later used to divide the samples into those that guided the classification and regression tree (CART) analysis and those set aside for subsequent accuracy assessment.

Field information for each sample segment was entered into a Global Positioning System (GPS)-linked ArcGIS field form developed specifically for this project by Tukman Geospatial. As displayed in Figures 26, the form provided access to the digital camera imagery and the segments and included the dichotomous key rules developed for the habitat classification scheme. The form's functionality also included automatic error checking.

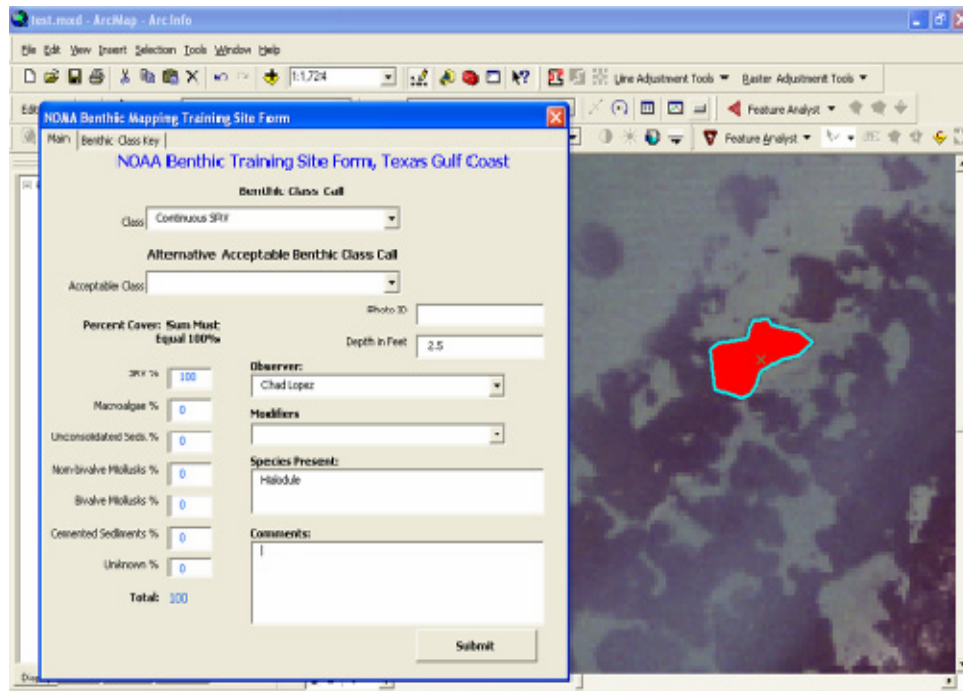


Figure 26. Showing the digital field form and the spatial site superimposed on the source imagery.



Figure 27. Field data entry setup in one of the Texas Parks and Wildlife Department boats. The link to the GPS receiver allows navigation directly to specific sites as displayed on the computer screen.

Field equipment used on each field trip included the following:

- Ruggedized laptop with all imagery, ancillary data, and the digital field form loaded
- GPS receiver with field points loaded
- Underwater video camera system
- Underwater digital camera
- Hard copy maps of the imagery
- Hard copy field forms

Because of the one-and-a-half-year time lapse between the date of imagery collection (late 2004) and the calibration trip (mid 2006), special attention was paid to understanding the extent and conditions in areas where changes were observed.

The Phase I calibration trips resulted in data collection at 583 field sample segments. Data on an additional 788 sample segments were collected through manual interpretation of the imagery for a total of 1,329 sample sites. A random number generator was then used to select and set aside

100 sites per benthic class for accuracy assessment, which were then divided into 50 sites per class for the sand or mud substrate types present on the Texas coast.

The Phase II trips resulted in data collection for 121 field samples for the Lower Laguna Madre and 115 samples for the San Antonio Bay system. More sample segments were collected through manual interpretation of the imagery. There were 161 office sites (sites selected based on visual interpretation of the imagery) collected for Lower Laguna Madre and 234 office sites for San Antonio Bay for a total of 182 and 349 respectively. A random number generator was then used to select and set aside 30 sites per benthic class per region (Lower Laguna Madre and San Antonio Bay) for accuracy assessment.

Image Segmentation

The first step in object-oriented classification is segmentation of the imagery. Imagery from each bay system was segmented using Definiens Professional software. Similar to the manual delineation of polygons in photo interpretation, segmentation algorithms delineate digital imagery into segments, or polygons, of similar pixels, that based on a user-defined set of inputs layers. In this project, the four ADS40 raw spectral bands (red, green, blue, and near infrared) were used as input layers into the image segmentation algorithm. Definiens Professional provides several parameters that users can choose to affect the size, detail, and shape of the resulting segments. These parameters include the following:

- Scale
- Color
- Shape
- Smoothness
- Compactness
- Input spectral bands from the source imagery.

Scale is an important driver of segmentation because it determines the relative size and number of polygons generated by the algorithm.

Segmentation runs were conducted on the Phase I data at a single scale. As the methods were refined, two segmentation runs were conducted on the Phase II data, the first at a large-scale factor for larger polygons and a second at a small-scale factor in select areas for smaller, more detailed polygons.

CART Analysis

CART (classification and regression tree) analysis was performed on the non-accuracy assessment sample data, the imagery, and ancillary data layers using See5 statistical software. CART analysis builds tree diagrams for predicting variables from categorical and continuous data (Breiman and others 1984). It “mines” the sample data and builds a set of if-then statements in hierarchical “trees,” which are rules that define the habitat classes. CART analysis is powerful because

- it can accept both continuous and categorical data inputs,
- the results are easy to interpret,
- unlike a maximum likelihood classifier, no assumptions are required concerning the distributions of the independent variables,
- it identifies simple and complex relationships between variables that other techniques might not uncover, and
- it forces consistency and analytical rigor into the segment labeling process.

To assess the efficacy of alternative sets of CART-generated rules, labels of the independent accuracy assessment sites were compared with their CART-generated labels in error matrices. An analysis of the error matrices provided a quantitative assessment of these classification rules before applying them to the entire project segment data set.

The following ancillary data sets were employed to support the CART analysis.

- ADS-40 NDVI
- Land-Water Mask
- NOAA bathymetry
- Landsat imagery

Draft Map Development

Following the analysis of the error matrices, input layers, and CART rules, the techniques that generated the highest accuracies were applied to the remaining image segments in ArcGIS to generate a draft map of benthic habitat. This draft map was lightly edited and reviewed by the project team.

DATA VALIDATION

Thematic Validation

Thematic validation for the Texas coastal data took place throughout the mapping and can be divided into two components: an internal statistically based accuracy assessment of the data by the Fugro Earthdata team and a subsequent validation assessment by NOAA and the Texas project partners. The first contractor assessment was intended to determine both deterministic and fuzzy accuracies (Gopal and Woodcock 1994) for each of the map classes using a stratified random sampling approach (Green and Congalton 2004). The second assessment was to assess the fitness-for-use by end users. Both components were completed for Phase I and Phase II of the project area.

A random sampling approach was taken to develop samples for accuracy assessment with a minimum of 30 samples per class (50 samples per class for both mud and sand systems in Phase I). These points were selected and visited during the signature development trips early in the project and held aside to test CART runs and finally validate the final habitat data set. Navigating directly to sample sites using GPS, underwater video and diving were used to determine the habitat present on the ground as with the signature development points. In the case of Annelid Reef, only three samples were collected since this was such a rare habitat. These points formed the initial sample set for accuracy assessment; however, additional points were also visited during the contractor's accuracy assessment field trips.

Accuracy Assessment

NOAA, Fugro EarthData team members, and State of Texas partners evaluated the draft maps to select sites for contractor accuracy assessment field trips. Areas to be visited in the field were chosen according to the following criteria:

- Class confusion identified in the draft map error matrix,
- Confused areas identified by the image analysts,
- Areas where field data were not collected during the previous calibration trip, and

- Comments on specific sites from NOAA and Texas personnel.

The accuracy assessment trips took place during the following dates for each region:

Aransas Bay, Copano Bay, Redfish Bay, January 22 – February 2, 2007
Corpus Christi Bay, Upper Laguna Madre,
and Baffin Bay

Lower Laguna Madre October 29 – November 1, 2007

San Antonio and Espiritu Santo Bays July 21, 2008

Editing and Post-Processing

Using information collected during the field trips and comments from NOAA and Texas end users, the benthic map data were thoroughly reviewed and manually edited. Editing focused on the correction of polygon labels, but line edits were also performed on some polygons where the boundaries between habitats needed adjusting. Also, dock and bridge structure polygons over benthic habitats were manually removed and mapped as the benthic habitat underneath the structures. Edge matching was also performed on adjacent processing region and bay systems. Once editing was complete, adjacent polygons with the same labels were dissolved, and the polygon boundaries were smoothed to reduce the stair step effect caused by the square boundaries of the image pixels. The resulting contractor-final map was then provided to NOAA and the Texas partners for review during their independent validation trip.

	Habitat Class	Reference Sites						Total	User's Accuracy	
		SRV	Unconsolidated Sediments	Bivalve Reef	Unknown Habitat	Emergent Marsh	Mangroves			Land
Map	SRV	245	68	7		9	1		330	74%
	Unconsolidated Sediments	14	175	4	1	4	1	3	202	87%
	Bivalve Reef			146		1			147	99%
	Unknown Habitat	1	13	4	161			1	180	89%
	Emergent Marsh					111	2	4	117	95%
	Mangroves					7	158		165	96%
	Land		2			20	3	125	150	83%
	Total	260	258	161	162	152	165	133	1291	
	Producer's Accuracy	94%	68%	91%	99%	73%	96%	94%		87%

Figure 28. Combined error matrix for all coastal bend bay systems.

Overall deterministic accuracy is quite high at 87%. Users and producers accuracies are generally above 80%. The classes with the most confusion are unconsolidated sediments and emergent marsh. Errors include confusion of unconsolidated sediments with SRV, especially in low-biomass areas. Emergent marsh is mainly confused with land vegetation, but it's also confused to some extent with mangroves, SRV, and unconsolidated sediments. This latter case is caused by the presence of mat algae on some sediments which produced a spectral response similar to emergent vegetation. Annelid reef was not included in the accuracy assessment due to the very small number and spatial autocorrelation of the sites. The Kappa coefficient for these data is 84.4%.

Final Validation

NOAA and the Texas partners conducted follow-up visits to the field to review the final product, clarify potential areas of confusion, and address any obvious potential errors that might still exist in the data. Three hundred fifty-four sites were selected for evaluation during the NOAA

validation trips over the entire project area. The majority were visited, although in certain instances, once a type of error or habitat was understood, subsequent visits to similar sites were not necessary. The field methods used by NOAA and the Texas partners were the same as used on earlier trips. Since the points selected for this final validation were targeted on areas of potential error they were not included in the error matrix above. The feedback from these visits was used to make final edits and compile the finished data sets.

Completion of the Final Data Sets

After the final edits were made, all the habitat polygons were combined into a single shapefile and then clipped out into individual areas for the following bay systems: San Antonio Bay, Espiritu Santo Bay, Aransas Bay, Copano Bay, Redfish Bay, Corpus Christi Bay/Nueces Bay, Upper Laguna Madre, Baffin Bay, Lower Laguna Madre-North, -Middle, and -South sections. Polygons do not overlap between adjacent bay systems, but are perfectly adjacent, resulting in no duplication of polygons or portions of polygons. This also allowed each polygon to be given a unique identification number that was unique both within each bay system and among all ten bay systems.

BAY SYSTEM MAP SHEETS

Map Sheet Tiling Framework

The following sections consist of individual map sheets organized by bay system and tiled on a systematic basis according to Digital Ortho Quarter-Quarter Quad (DOQQ-Q) boundaries. The sheets follow a naming convention with the name of the quadrangle followed by the quarter and then if needed, the quarter within it. For example; Rockport SE-SW, which is the southwest quarter of the southeast quarter of the Rockport 7.5' quadrangle.

Each section begins with an index map showing the tile layout and numbering. The numbering of the tiles reflects the page numbers of the actual map sheets that follow. In several cases a tile was not included where no benthic habitat was mapped, such as the center of large water bodies or on the seaward side of the barrier islands.

Map Sheet Abbreviations

The following abbreviations have been used on the map sheets in this document to save space and ensure that each sheet is uncluttered and easily read.

CP =	Coastal Preserve
WMA =	Wildlife Management Area
SP =	State Park
NWR =	National Wildlife Refuge
WR =	Wildlife Refuge

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Texas Commission on Environmental Quality (TCEQ). 2008. "2008 Guidance for Assessing and Reporting Surface Water Quality in Texas." Texas Commission on Environmental Quality. Austin, TX.

Appendix A: Additional Websites on Seagrass and Oyster Reef Mapping Projects

Seagrasses

Barataria-Terrebonne National Estuary Program (BTNEP):

http://educators.btnep.org/client_files/editor_files/Submerged_Aquatic_Vegetation_BTNEP.pdf

Center for Research in Water Resources (CRWR):

www.crwr.utexas.edu/gis/gishydro03/Classroom/trmproj/Fellows/GIS%20in%20Water%20Resources%20-%20Fall%202002%20Term%20Project.htm

Coastal Bend Bays and Estuaries Program (CBBEP):

www.cbbep.org/publications/virtuallibrary/factsheet/FS204/factsheet4.HTM

Fish and Wildlife Research Institute (FWRI):

http://research.myfwc.com/features/category_sub.asp?id=2649

Minerals Management Service (MMS):

www.mms.gov/itd/pubs/1999/99-0050/mssav.htm

National Biological Information Infrastructure (NBII):

www.nbio.gov/portal/server.pt?open=512&objID=782&&PageID=2692&mode=2&in_hi_userid=2&cached=true

National Aeronautics and Space Administration (NASA):

http://gcmd.nasa.gov/records/GCMD_brdsnrc0005.html

National Oceanic and Atmospheric Administration (NOAA):

www.oar.noaa.gov/spotlite/archive/spot_lsu.html

NOAA Coastal Services Center:

www.csc.noaa.gov

www.csc.noaa.gov/crs/rs_apps/issues/sb_louis.htm

Tampa Bay Estuary Program (TBEP):

www.tbep.org/portrait/habitats.html

Teamseagrass:

<http://teamseagrass.blogspot.com/2009/05/seagrasses-in-tampa-bay-bouncing-back.html>

Texas Parks and Wildlife Department (TPWD):

www.tpwd.state.tx.us/landwater/water/habitats/seagrass/

The Nature Conservancy (TNC):

www.saveourseagrass.org/

U.S. Fish and Wildlife Service (USFWS):

www.fws.gov/texascoastalprogram/seagrass.htm

U.S. Geological Survey (USGS):

<http://sdms.cr.usgs.gov/pub/alsav.html>

www.nwrc.usgs.gov/factshts/017-00.pdf

Virginia Institute of Marine Science (VIMS):

<http://web.vims.edu/bio/sav/>

Oysters

NOAA Coastal Services Center:

www.csc.noaa.gov/crs/rs_apps/issues/scoysters.htm

South Carolina Department of Natural Resources (DNR):

www.dnr.sc.gov/GIS/descoysterbed.html

Texas General Land Office (TGLO):

www.glo.state.tx.us/nri/data/index.html

Appendix B: Tables of Areal Coverage by Habitat Types

Table B-1. Summary of the areal extent of benthic habitat types mapped in San Antonio Bay. Areal values for the habitats with modifiers include the areal data for the modifiers. SRV=Submerged Rooted Vegetation.

Habitat /Modifiers	Hectares	Acres
Bivalve Reef	625.759	1,546.285
Continuous SRV	2,407.001	5,947.830
Patchy SRV	155.084	383.221
Tidal Marsh	4,054.225	10,018.208
Tidal Swamp	43.524	107.550
Unconsolidated Sediments	3,605.624	8,909.690
Drift Algae	101.924	251.860
Mat Algae	5.450	13.468
Shell Hash	3.279	8.102
Total	10,891.217	26,912.783

Table B-2. Summary of the areal extent of benthic habitat types mapped in Espiritu Santo Bay. Areal values for the habitats with modifiers include the areal data for the modifiers. SRV=Submerged Rooted Vegetation.

Habitat /Modifiers	Hectares	Acres
Bivalve Reef	281.031	694.442
Continuous SRV	5,936.281	14,668.871
Patchy SRV	860.403	2,126.101
Tidal Swamp	878.203	2,170.088
Tidal Marsh	2,287.245	5651.906
Unconsolidated Sediments	4,159.424	10278.162
Drift Algae	9.319	23.027
Mat Algae	1,64.676	406.924
Shell Hash	71.369	176.357
Unknown	85,363.704	210,938.306
Total	99,766.292	24,6527.876

Table B-3. Summary of the areal extent of benthic habitat types mapped in Aransas Bay. Areal values for the habitats with modifiers include the areal data for the modifiers. SRV=Submerged Rooted Vegetation.

Habitat /Modifiers	Hectares	Acres
Bivalve Reef	2,458.397	6,074.832
Drift Algae	16.790	41.490
Mat Algae	2.252	5.564
Shell Hash	1,109.856	2,742.515
Continuous SRV	2,955.845	7,304.051
Drift Algae	260.246	643.081
Mat Algae	87.251	215.602
Shell Hash	14.410	35.609
Wrack	1.972	4.872
Patchy SRV	742.384	1834.471
Drift Algae	3.876	9.578
Mat Algae	0.673	1.663
Shell Hash	1.044	2.581
Tidal Marsh	2,353.984	5,816.821
Drift Algae	0.087	0.215
Shell Hash	0.151	0.373
Tidal Swamp	50.264	124.206
Unconsolidated Sediments	3,214.042	7,942.071
Shell Hash	2.514	6.213
Drift Algae	13.788	34.070
Mat Algae	469.181	1,159.372
Unknown	28,531.571	70,503.048
Drift Algae	14.140	34.940
Total	40,306.487	99,599.499

Table B-4. Summary of the areal extent of benthic habitat types mapped in Copano Bay. Areal values for the habitats with modifiers include the areal data for the modifiers. SRV=Submerged Rooted Vegetation.

Habitat /Modifiers	Hectares	Acres
Bivalve Reef	482.150	1191.419
Shell Hash/Shell	192.473	475.610
Continuous SRV	696.617	1,721.379
Drift Algae	14.485	35.794
Mat Algae	248.510	614.082
Patchy SRV	287.669	710.847
Drift Algae	17.137	42.346
Mat Algae	30.090	74.354
Tidal Marsh	1,087.721	2,687.818
Mat Algae	3.596	8.887
Tidal Swamp	0.000	0.000
Unconsolidated Sediments	2,838.360	7,013.740
Drift Algae	0.184	0.455
Mat Algae	99.534	245.954
Shell Hash	0.566	1.400
Unknown	17,080.407	42,206.606
Total	22,472.926	55,531.809

Table B-5. Summary of the areal extent of benthic habitat types mapped in Redfish Bay. Areal values for the habitats with modifiers include the areal data for the modifiers. SRV=Submerged Rooted Vegetation.

Habitat /Modifiers	Hectares	Acres
Bivalve Reef	41.439	102.399
Continuous SRV	4,998.622	12,351.863
Drift Algae	4.294	10.611
Patchy SRV	773.577	1911.550
Drift Algae	0.152	0.374
Tidal Marsh	71.458	176.578
Tidal Swamp	766.394	1893.801
Drift Algae	0.019	0.048
Unconsolidated Sediments	2,490.264	6,153.576
Drift Algae	283.446	700.409
Mat Algae	66.321	163.883
Shell Hash	53.939	133.287
Unknown	3,637.940	8,989.545
Total	12,779.694	31,579.311

Table B-6. Summary of the areal extent of benthic habitat types mapped in Corpus Christi Bay. Areal values for the habitats with modifiers include the areal data for the modifiers. SRV=Submerged Rooted Vegetation.

Habitat/Modifiers	Hectares	Acres
Bivalve Reef	38.534	95.220
Continuous SRV	1,612.055	3,983.474
Drift Algae	10.041	24.813
Patchy SRV	367.978	909.294
Drift Algae	0.067	0.165
Tidal Swamp	15.357	37.947
Tidal Marsh	130.094	321.468
Unconsolidated Sediments	3,347.512	8271.881
Mat Algae	740.946	1,830.917
Unknown	44,093.671	108,957.835
Total	49,605.200	122,577.119

Table B-7. Summary of the areal extent of benthic habitat types mapped in Nueces Bay. Areal values for the habitats with modifiers include the areal data for the modifiers. SRV=Submerged Rooted Vegetation.

Habitat /Modifiers	Hectares	Acres
Bivalve Reef	256.330	633.406
Shell Hash	33.823	83.578
Continuous SRV	239.962	592.960
Patchy SRV	72.540	179.251
Mat Algae	0.144	0.357
Tidal Swamp	0.303	0.748
Tidal Marsh	14.221	35.142
Unconsolidated Sediments	349.213	862.924
Mat Algae	68.357	168.915
Shell Hash	50.076	123.741
Total	932.57	2304.43

Table B-8. Summary of the areal extent of benthic habitat types mapped in the Upper Laguna Madre. Areal values for the habitats with modifiers include the areal data for the modifiers. SRV=Submerged Rooted Vegetation.

Habitat/Modifiers	Hectares	Acres
Annelid Reef	0.235	0.581
Bivalve Reef	16.587	40.988
Continuous SRV	22,213.204	54,890.023
Attached Algae	1.644	4.063
Patchy SRV	2,032.428	5,022.238
Drift Algae	6.187	15.289
Attached Algae	1.439	3.557
Tidal Swamp	0.667	1.649
Tidal Marsh	114.636	283.271
Unconsolidated Sediments	13,994.162	34,580.327
Drift Algae	21.901	54.119
Mat Algae	397.432	982.076
Drift Wrack	37.174	91.859
Unknown	6,831.164	16,880.175
Total	45,203.08	11,1699.25

Table B-9. Summary of the areal extent of benthic habitat types mapped in Baffin Bay. Areal values for the habitats with modifiers include the areal data for the modifiers. SRV=Submerged Rooted Vegetation.

Habitat /Modifiers	Hectares	Acres
Annelid Reef	11.890	29.380
Seagrass	2.819	6.966
Continuous SRV	1,848.450	4,567.620
Drift Algae	89.363	220.820
Mat Algae	55.542	137.247
Patchy SRV	446.397	1,103.071
Drift Algae	12.845	31.741
Mat Algae	8.819	21.793
Tidal Marsh	33.033	81.627
Mat Algae	25.155	62.159
Unconsolidated Sediments	5,119.603	12,650.816
Drift Algae	5.591	13.816
Mat Algae	1,105.635	2,732.084
Salt Flat	70.289	173.688
Shell Hash	1.024	2.531
Unknown	19,471.966	48,116.275
Drift Algae	1.232	3.045
Total	26,931.34	66,548.79

Table B-10. Summary of the areal extent of benthic habitat types mapped in the Lower Laguna Madre. Areal values for the habitats with modifiers include the areal data for the modifiers. SRV=Submerged Rooted Vegetation.

Habitat /Modifiers	Hectares	Acres
Annelid Reef	0.091	0.226
Bivalve Reef	67.545	166.908
Continuous SRV	42,613.181	105,299.465
Patchy SRV	1,932.738	4,775.900
Tidal Swamp	282.917	699.103
Tidal Marsh	1,908.477	4,715.950
Unconsolidated Sediments	86,720.815	21,4291.801
Drift Algae	51.090	126.246
Mat Algae	3,8001.854	9,3904.627
Drift Wrack	4.992	12.337
Shell Hash	11.132	27.507
Unknown	17,510.652	43,269.763
Total	151,036.42	373,219.11