OCS Study
BOEM 2020-002
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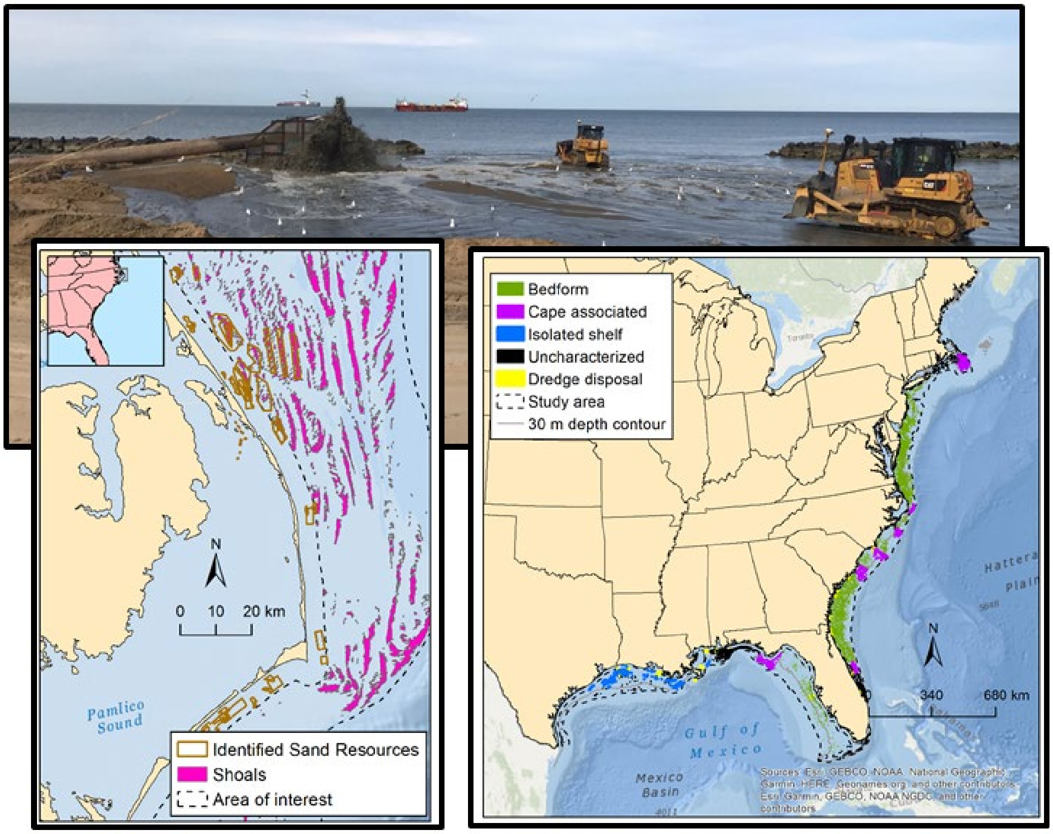
Regional Essential Fish Habitat Geospatial Assessment and Framework for Offshore Sand Features

Volume 2: Shoal Identification and Classification of Sand Resources



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Regional Essential Fish Habitat Geospatial Assessment and Framework for Offshore Sand Features

Volume 2: Shoal Identification and Classification of Sand Resources

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DISCLAIMER

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CITATION

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List of Abbreviations and Acronyms

BC	Biotic Component
BGN	Board on Geographic Names
BOEM	Bureau of Ocean Energy Management
BPI	bathymetric position index
CATAMI	Collaborative and Automated Tools for Analysis of Marine Imagery
CMECS	Coastal Marine Ecological Classification Standard
CRM	Coastal Relief Model
cy	cubic yard(s)
DEM	digital elevation model
DOC	Department of Commerce
DOI	Department of the Interior
EFH	Essential Fish Habitat
GC	Geoform Component
GMFMC	Gulf of Mexico Marine Fisheries Council
GNS	GEOnet Names Server
ha	hectare
HAPC	Habitat Areas of Particular Concern
km	kilometer(s)
m	meter(s)
mm	millimeter(s)
MMIS	Marine Minerals Information System
NGA	National Geospatial-Intelligence Agency
NGDC	National Geophysical Data Center
NCCOS	National Centers for Coastal Ocean Science
nm	nautical mile(s)
NOAA	National Oceanic and Atmospheric Administration
OCS	Outer Continental Shelf
SC	Substrate Component
ShoalMATE	Shoal Mapping Assessment Tool for EFH
SME	subject matter expert
TNC	The Nature Conservancy
US	US Geological Survey
US EPA	US Environmental Protection Agency
USACE	US Army Corps of Engineers
USGS	US Geological Survey

Abstract

The demand is increasing in the United States for marine sand resources to mitigate risks of coastal erosion from modifications to the shoreline due to coastal development or impacts of waves and currents during major storms. As sources for sediment in the nearshore are being depleted, there is increased demand for sand resources from the Outer Continental Shelf (OCS). Extensive studies have helped elucidate the dynamics and geomorphological characteristics of some prominent shoals, but we lack a broader understanding of the extent and types of shoals that exist along the Gulf and Atlantic Coasts of the OCS. Furthermore, offshore sand features have typically been characterized in a geological framework, and we lack descriptors for sand features that contribute to Essential Fish Habitat (EFH) descriptions. This volume comprises two components. First, we developed a seabed classification model that identifies and delineates potential sand shoals using broadly available, unified digital elevation models for the seafloor along the Gulf of Mexico and Atlantic coastlines from 3 nautical miles (nm) from shore to the 50-m depth contour. Distance from shore as well as seafloor complexity and relief metrics, derived from the Coastal Relief Model, were used to classify offshore areas of relative higher relief and produce polygons showing geomorphological features consistent with sand shoals, ridges, and swales. Newly created maps depict bedforms, shoal complexes, and unclassified features along the Gulf and Atlantic OCS. Recognition of these features in the context of EFH and sand resource demand can aide in improved planning and conservation recommendations for sand dredging activities. Three workshops were hosted with biological and geological subject matter experts to define criteria for classifying shoals and other sand features. We then used this new classification scheme to attribute sand shoals according to characteristics such as geoforms and environmental criteria to develop a new scheme. This new classification scheme was formalized under the Coastal Marine Ecological Classification Standard (CMECS) and proposed for adoption as a new schema for classifying OCS shoals.

1 Introduction

The demand for marine sand resources is increasing in the United States (Drucker et al. 2004) and worldwide (Charlier and Charlier 1992; de Jong et al. 2014; Kim et al. 2008; La Porta et al. 2009). The Netherlands alone uses an estimated 24 million m^3 (31 million cy) of dredged sand annually, and the amount is expected to grow rapidly with rising sea level (de Jong et al. 2014). In the United States, coastal and offshore marine sands are commonly used for beach renourishment, barrier island restoration, and wetland restoration. As human populations and development expands along the coastline, erosion will continue to bring challenges to ensuring sustainability in the coastal zone. The restoration and maintenance of beaches, barrier islands, and other coastal infrastructure will require substantial sediment resources. Although prior sand mining activities have focused on nearshore sand sources (i.e., in state waters), the dredging of Outer Continental Shelf (OCS) sand resources is likely to increase in the near future as nearshore sand resources are depleted (Nairn et al. 2004). Throughout this report, we use the term "sand" to broadly characterize sediment resources, and we recognize that sediment dredging may include a variety of grain sizes depending on the application.

Sand resource mapping in offshore waters has been ongoing for decades, and cooperative agreements have been established between Federal and state governments to synthesize existing and new information, including the mapping of sand shoals appropriate for sand mining (Drucker et al. 2004). Marine sand dredging occurs in relatively shallow waters (≤ 50 m), often within ridge and swale complexes where large volumes of sand can be extracted over relatively small areas. As of 2019, all 17 Atlantic and Gulf of Mexico coastal states have cooperative agreements with BOEM to identify available sand resources. As of 2017, there were no BOEM sand and gravel leases in New England and New York, but storms and erosion have led to an anticipation of offshore sand dredging in the region. For example, Maine, New Hampshire, Massachusetts, Rhode Island, and New York all signed cooperative agreements to evaluate sand resources in 2014 following Hurricane Sandy. The overall strong upward trend of OCS sand dredging necessitates a greater strategic vision for managing sand resources as a whole rather than the site-by-site approach that has been undertaken to this point. Current geophysical and geotechnical survey and other seabed mapping activities have only covered a small percentage of the OCS and vary in extent across geographic regions, leaving major gaps in knowledge of the location and extent of sand resources.

Sand shoals are also habitats for economically important fisheries. Along the United States (US) Atlantic and Gulf of Mexico Coasts, sand shoals are used by juvenile reef fish, shrimp, coastal pelagic fish species during seasonal spawning migrations, and as feeding grounds for demersal fishes and sharks (Rutecki et al. 2014). Particular shoals features have been designated as EFH, and conservation recommendations are provided for special considerations that minimize environmental impacts caused by commercial uses of the ocean and seafloor. The Bureau of Ocean Energy Management (BOEM), as part of the US Department of the Interior, is responsible for the management and development of sand resources on the OCS. All proposed sand dredging projects require prior analysis of impacts to marine resources using the best available science to understand and mitigate environmental impacts when possible. The mapping of shoals will help assess potential impacts of sand dredging, assist efforts to understand species' habitat relationships with shoals, and set the stage for a broader classification of marine unconsolidated sediment ecosystems. Lastly, better information on the extent of possible sand resources will inform strategic decisions about mineral resource use and the availability to meet demand.

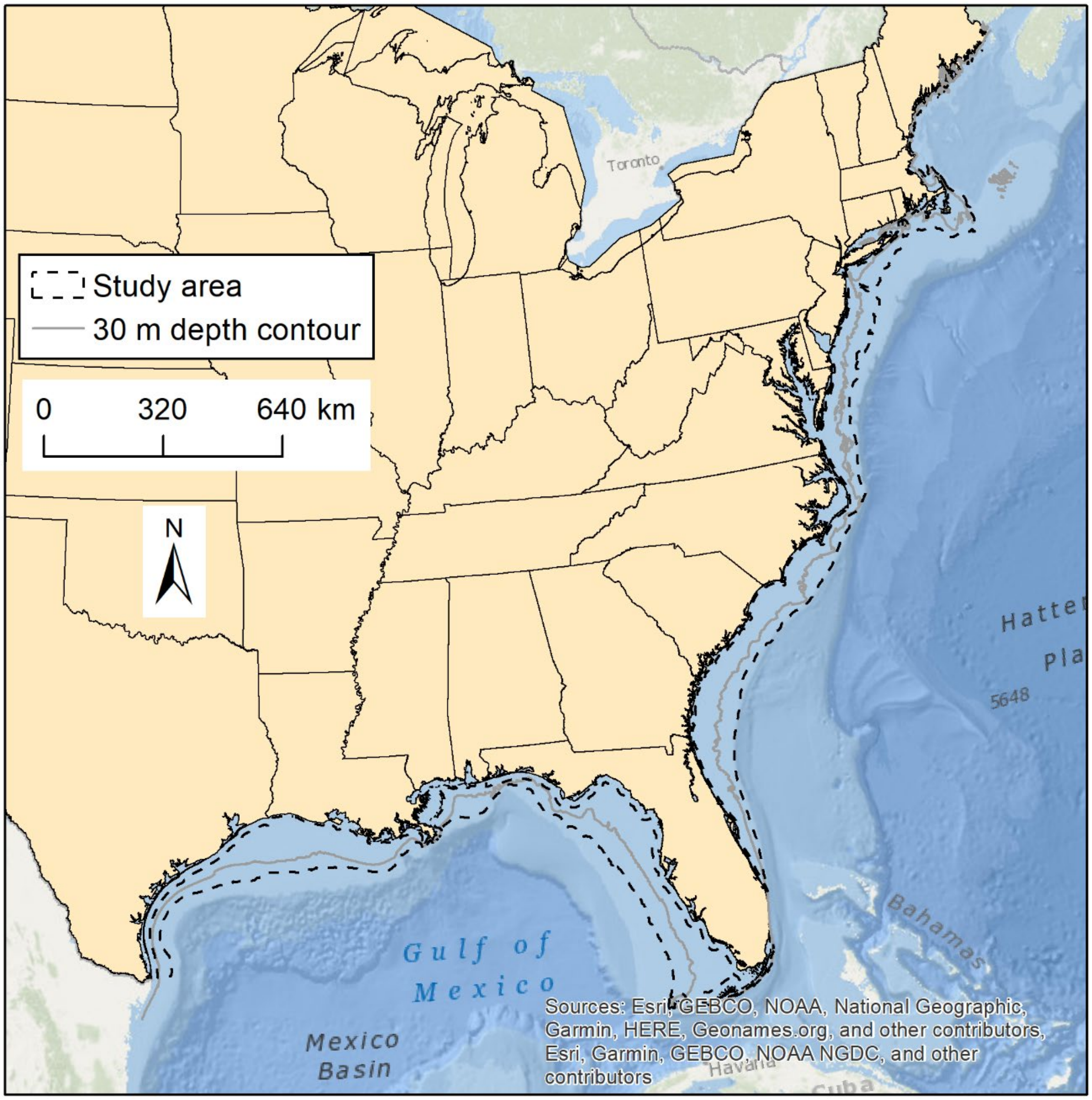
Shoals are common geologic features on the continental shelf and are defined as sand, or other unconsolidated material, that result in shallower water depths than surrounding areas (Rutecki et al. 2014). Other terms noted for shoals include underwater “ridges,” “banks,” or “bars.” Characteristics of shoals include crests, troughs, areas with slope, and varying sediment substrates (Vasslides and Able

2008). In the simplest terms, shoals are distinguished as areas of topographic relief compared to flat, low-relief unconsolidated sediments. Bathymetric highs are often accompanied by troughs and swales. This report follows an intensive literature review by Rutecki et al. (2014), which provides extensive examples on the geology, geography, and general biological values of sand shoals. Although these definitions and case studies were sufficient to develop an understanding of the importance of shoals in coastal geology and as fish habitat, we still lack a method that delineates the distribution and extent of shoals on the OCS, as well as a unified classification scheme for characterizing sand features in terms of geomorphology and potential habitat value. The primary objective of this chapter was to develop spatially explicit models that classify, and whenever possible verify, the location and extent of potential shoals of the United States' OCS spanning the northwest Atlantic Ocean and the Gulf of Mexico. The second objective was to identify attributes that distinguish shoals from other marine geomorphic features and propose a classification scheme compatible with the Coastal and Marine Ecological Classification Standard (CMECS) (FGDC (Federal Geographic Data Committee) 2012). The classification scheme and shoal layers developed in this volume were incorporated into the interactive mapping and reporting tool ShoalMATE (Shoal Mapping Assessment Tool for EFH), which is described in more detail in Volume 4.

2 Identifying Shoals on the OCS

2.1 Study Area

The landward boundary of the study area was defined by the Outer Continental Shelf Lands Act, which distinguishes Federal and state managed waters. Federal waters are those ≥ 3 nm from the shoreline, with the exception of Texas and the Gulf Coast of Florida where Federal waters are defined as ≥ 9 nm from the shoreline. The oceanic boundary of the study area was defined by a 50 m contour line (**Figure 2-1)**, which is the deepest extent of anticipated dredging activities, although 30 m is currently the deepest extent of existing dredge activities. The contour line was derived from the Coastal Relief Model of the National Oceanic and Atmospheric Administration (NOAA) (NOAA National Centers for Environmental Information 2010). To account for potential regional differences in seafloor geomorphology, separate analyses were conducted for three regions: Greater Atlantic, South Atlantic, and Gulf of Mexico. Because of concurrent fish research, the boundaries of the three regions generally coincided with Federal fishery management council jurisdictions and NOAA's Essential Fish Habitat (EFH) designations. The Greater Atlantic region spanned from the northern extent of Maine to just south of Cape Hatteras, North Carolina. The South Atlantic region extended from Cape Hatteras, North Carolina, southward to the Florida Keys. The Gulf of Mexico region included Texas eastward through the Florida Keys.



Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors, Esri, Garmin, GEBCO, NOAA NGDC, and other contributors

Figure 2-1. Geographic boundaries for the study area (dashed line) in the US Gulf of Mexico and Atlantic Coasts, extending from the offshore state/Federal boundary to 50-m depths.
Map also shows the 30-m depth contour, which is the deepest extent of current dredging activities.

2.2 Source Data and Spatial Data Variables

Existing bathymetric digital elevation models (DEMs) provided the primary source data for this study. Bathymetry for the central and western Gulf of Mexico was derived from NOAA's Coastal Relief Model (NOAA National Centers for Environmental Information), which characterized waters offshore of Texas, Louisiana, Mississippi, and Alabama. However, several large errors were prominent offshore of Florida. Therefore, we used sounding data summarized and developed into a 50-m raster grid by the US Geological Survey (Robbins et al. 2007). To be consistent with the other datasets, these data were resampled to a 90-m resolution with bilinear resampling. For the South Atlantic, we used a bathymetry dataset derived as part of The Nature Conservancy's South Atlantic Marine Bight Assessment (Conley et al. 2017). They synthesized 4.7 million depth sounding points obtained from the National Geophysical

Data Center's (NGDC's) Coastal Relief Model (CRM) (NOAA National Centers for Environmental Information 2010). The initial hydrographic surveys compiled by NOAA were completed between 1851 and 1965 and from survey data obtained digitally on National Ocean Service survey vessels since 1965 (NOS (National Ocean Service) 2008). The Nature Conservancy (TNC) used only data after the 1950s, and kriging was used to interpolate among sounding points (Conley et al. 2017). Despite these data being the best available for the South Atlantic, a few notable errors persisted. We updated a 1,600-km^2 and a 400-km^2 region offshore of northeastern North Carolina with sounding points acquired in 2016 (NOAA National Centers for Environmental Information 2016). To be consistent throughout the region, we used the same kriging methods conducted by TNC. Bathymetry data for the Greater Atlantic was simply obtained from the CRM (NOAA National Centers for Environmental Information 2010). Where the South Atlantic bathymetry overlapped with the Greater Atlantic study area (Virginia and northeast North Carolina), we used the South Atlantic bathymetry because it had already been improved with recent data. All spatial data were converted to the North America Alberts Equal Area Conic map projection. All data were maintained at 90-m resolution, and analyses were conducted with ArcGIS 10.6 (ESRI, Redlands, CA).

Where sand resources are found in topographic mounds such as shoals or ridges, localized spatial models have typically used relatively coarse (> 10-m horizontal cell size) DEMs to detect anomalies in the seafloor using predictors, such as slope or rugosity, to locate seabed forms consistent with shoals (Knorr 2017). In contrast, we used an unsupervised classification method for mapping shoals with data on depth, standard deviation of depth, slope, distance to shoreline, and the bathymetric position index (BPI) as key variables. In addition to the depth measures directly provided by bathymetry, we used the Benthic Terrain Modeler (Wright et al. 2012) to derive slope (3 x 3 cells) and the BPI (27 x 27 cells for Atlantic; 71 x 71 cells for Gulf of Mexico) (**Figure 2-2**). We selected the BPI analysis scale by initially exploring possibilities for each region. The relatively narrow shoals of the Atlantic became distinguished at a 27 x 27 cell analysis window, whereas shoals in the Gulf of Mexico were relatively wide and were distinguished by a 71 x 71 cell analysis window. The standard deviation of depth (SD depth) was computed with the Spatial Analyst, a focal statistics tool with a 9 x 9 cell analysis window. Distance to shoreline was calculated by back-transforming boundaries of the Submerged Lands Act (NOAA National Ocean Service, Office for Coastal Management 2016), which is set at a distance of 3–9 nm from the shoreline, depending on the state. We used the buffer tool to re-create the approximate shoreline boundaries, and then we calculated the Euclidean distance from the shoreline to the entirety of the study area.

2.3 Delineation of Geomorphic Features

After examining bathymetry-derived variables and visually inspecting the large-scale geomorphological patterns along the OCS, we restricted the analyses to waters ≤ 40 m of depth because deeper waters were often influenced by the increasing slope at the continental shelf break, which differed dramatically from the geomorphology on the shelf. Depths from 40 to 100 m are typically characterized by emergent rocky outcrops, ledges, and areas of high relief and steep slope. We excluded this area to constrain the bathymetry-derived variables to those more typical on the shelf. We standardized all predictor variables by subtracting the mean and dividing by the standard deviation of the raster layer. The subsequent data distribution had a mean of approximately zero and a standard deviation of one. We used the standardized predictor variables as inputs into the ArcGIS ISO Cluster Unsupervised Classification, which identifies clusters of cells with similar attributes. In this method, the user defines the number of groups to be classified. We ran the tool iteratively with the number of output classifications ranging consecutively from 2 to 10. Given the lack of defined boundaries of shoals, we had the goal of creating the fewest classification classes possible to simplify the identification of shoals and other geomorphic features. The minimum cells per classification were set at 1,000, and half the cells were used to train the classification.

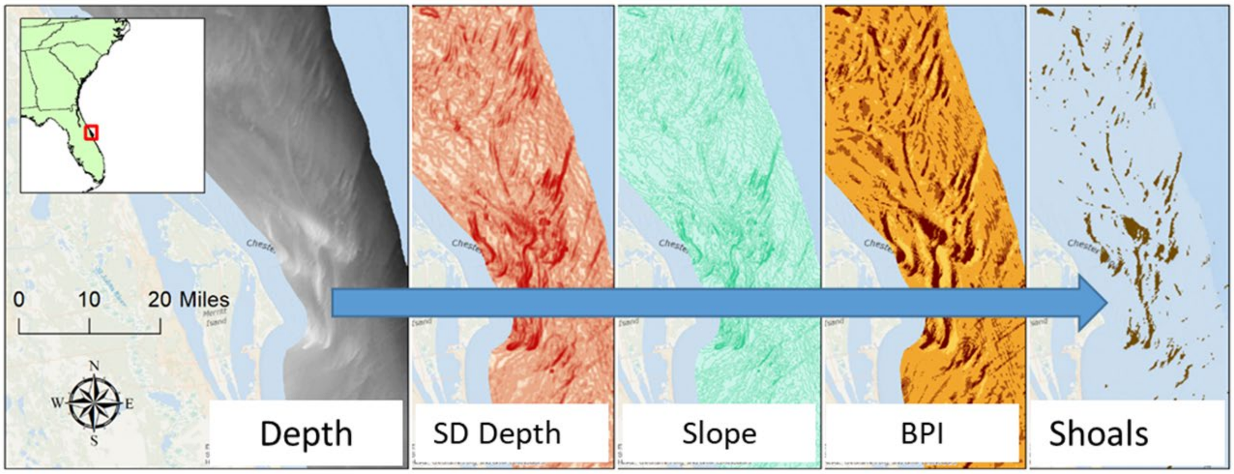


Figure 2-2. Examples of seafloor complexity metrics derived from bathymetry (depth) and used to delineate sand features and shoals.
SD depth = standard deviation of depth, BPI = bathymetric position index. The arrow represents the process of deriving three surfaces from Depth to classify features as Shoals. See text for descriptions for statistical assumptions for each derived surface.

After the initial identification, we used an eight-neighbor majority filter to remove small, isolated features. Based on the locations of a few known sand shoals (e.g., Ship Shoal in Gulf of Mexico, cape-associated shoals in Atlantic) and preliminary descriptive statistics, we classified features into “shoal,” “swale,” “high slope,” and “non-shoal.” Additionally, a minimum mapping unit of 5 hectare (ha) was used for shoal and swale classes in the Atlantic because 5 ha was the minimum size of shoal geomorphology identified in a recent review of sand shoals (Rutecki et al. 2014). For the Gulf of Mexico, a 20-ha minimum was used (see details below). All features below these size thresholds were removed, which further removed isolated cells.

For the Gulf of Mexico, the unsupervised classification resulted in nine classes, which included six labeled as “other seabed.” We removed classified shoals, swales, or high slopes that were parallel and continuous with a slope contour, which were particularly evident offshore of Texas, Louisiana, and the Florida Keys. These features were often adjacent to the boundary of bathymetry data and where bathymetry surfaces appeared relatively coarse. To further address this issue, we removed classifications with a perimeter to area ratio of > 10; this resulted in the smallest classification of shoal or swale being 20 ha in size. Additionally, the two features identified as “high slope” were removed because they had such an extremely high slope that it was likely due to bathymetry errors rather than a true seabed feature. The two features removed included an area depicted as a large hole and a classified shoal/swale area > 120 km offshore of Florida (northwest of Tampa Bay) and an area in waters well known as a natural, rocky reef that had been repeatedly sampled as part of a reef fish surveys. The remaining features were aggregated into a single class called “shoals” or “swales”. Statistics derived from the seafloor bathymetry are shallower in depth, higher slope, higher SD of depth and higher BPI than the surrounding seafloor (**Table 2-1**). Shoals were mapped throughout the Gulf of Mexico (**Figure 2-3**). Later in this volume, we further classify to shoal types using a new shoal classification scheme.

The South Atlantic shoals could be distinguished from regular bathymetric contours with a minimum of six classifications, and seven classifications distinguished both shoals and swales. With this methodology, an additional non-flat classification was created that depicted areas of extremely high slope and SD depth, as well as a positive BPI. Many of these features were sloping areas on the edge of shoals; however, we removed polygons parallel to the shelf break in Florida because these areas were part of the broader shelf geology. A few of these sloping features were in, or surrounding, holes; these were also removed from the shoal classification. We removed a circle-shaped classified shoal near Cape Hatteras, North Carolina, which was shown to be erroneous data in the raw CRM. We also removed erroneously classified shoal and swale features from the Florida Keys region because this geography is dominated by coral reefs and hard bottom as is characterized by the designated Habitat Areas of Particular Concern (HAPCs). The misclassification of shoals is likely because of similar characteristics, including relatively high depth heterogeneity, slope, and a positive BPI. Shoals in the South Atlantic, like the Gulf of Mexico, were distinct from the surrounding seafloor (**Table 2-1**, **Figure 2-3)**. For the Greater Atlantic, all shoals and swales were readily identifiable with four classes. Greater Atlantic shoals were similar distinct from the surrounding seafloor (**Table 2-1**, **Figure 2-3).**

Table 2-1. Variables used to delineate sand shoals via an unsupervised classification, descriptive statistics presented as mean ± (SD) for classified shoals, swales, and the entire dataset analyzed.

Analyses were conducted independently for each region and then combined.

		Greater Atlantic			South Atlantic			Gulf of Mexico		
Variable	**Scale of analysis (90-m cells)**	**Shoal**	**Swale**	**Entire seafloor**	**Shoal**	**Swale**	**Entire seafloor**	**Shoal**	**Swale**	**Entire seafloor**
Depth (m)	1	-20.87 (6.65)	-28.71 (8.26)	-28.11 (7.95)	-20.35 (6.65)	-26.45 (8.17)	-24.62 (8.42)	-19.93 (8.20)	-31.52 (7.17)	-24.21 (9.59)
SD of depth	9 x 9	1.32 (0.54)	2.46 (1.56)	0.67 (0.72)	0.99 (0.51)	1.72 (1.15)	0.49 (0.54)	0.53 (0.29)	1.33 (1.46)	0.23 (0.40)
Slope	3 x 3	0.39 (0.22)	0.79 (0.63)	0.15 (0.26)	0.29 (0.24)	0.54 (0.42)	0.11 (0.20)	0.14 (0.13)	0.41 (060)	0.04 (0.14)
Distance to shoreline (km)	NA	25.46 (13.78)	31.19 (16.60)	29.61 (17.34)	29.83 (17.31)	37.49 (20.92)	38.10 (22.44)	31.10 (15.02)	38.14 (21.84)	48.85 (27.49)
Bathymetric position index	Gulf of Mexico: 71 x 71; Atlantic: 27 x 27	2.49 (1.92)	-1.00 (3.88)	0.36 (1.62)	2.22 (1.27)	-0.56 (2.28)	0.32 (1.10)	2.41 (0.89)	-0.65 (2.92)	0.21 (1.15)

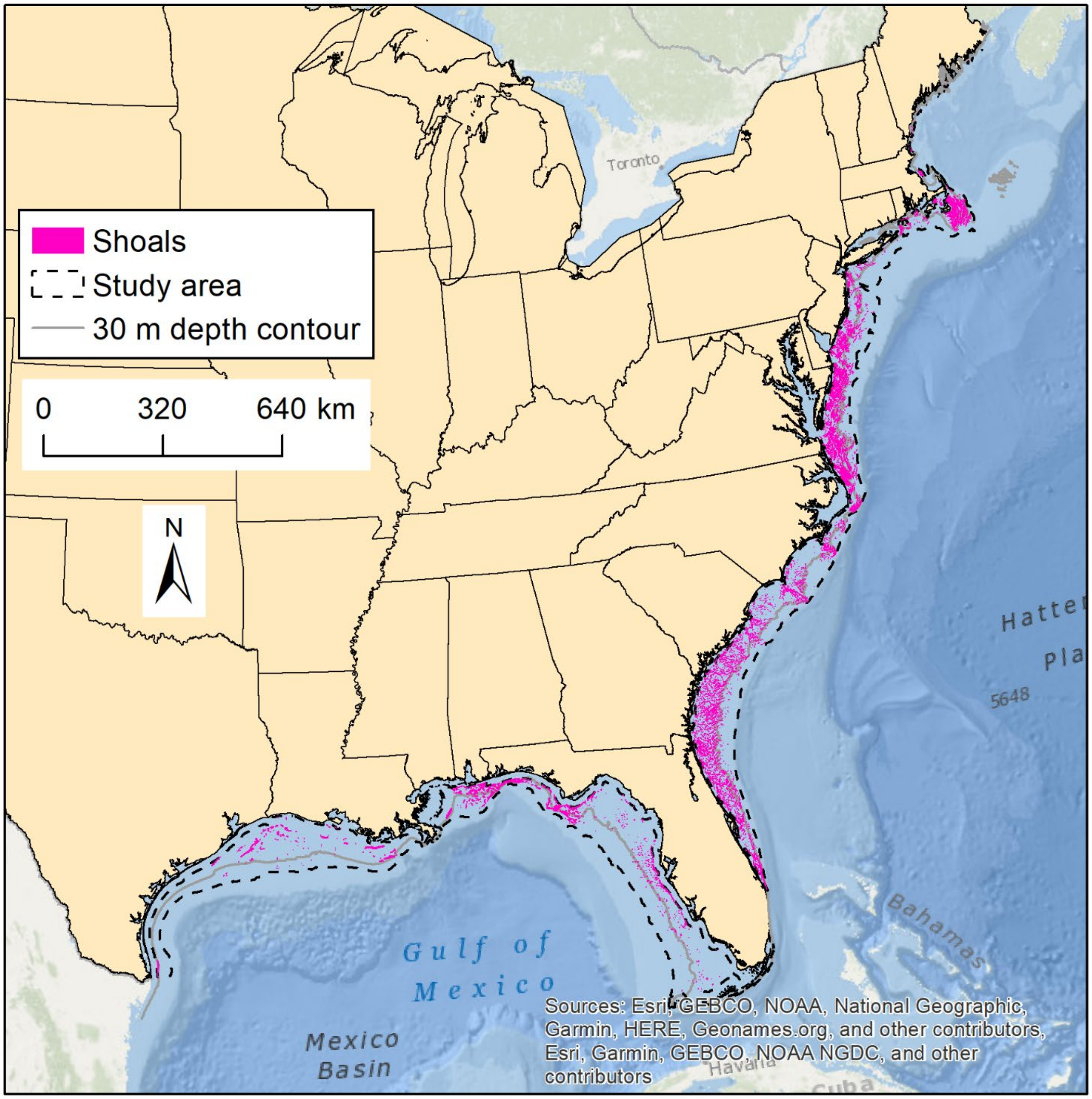


Figure 2-3. Delineated shoal features throughout the study area in the Gulf of Mexico and Atlantic OCS.

The dashed line indicates the study area of Federal waters to a maximum of 50-m depth. A 30-m depth contour also included as reference for deepest existing dredging project.

3 Classifying OCS Shoal and Sediment Resources

3.1 Goals and Design of the Shoal Classification Scheme

Having successfully identified shoals through semi-automated means, the next step was to group them into distinct classes that characterize their spatial location in the seascape, their geological origin and the environmental processes at work in their environment. This additional contextual information, conveyed through a classification system, is important to fully understanding the habitat value of these features. The classification system described in this section was based on physical and spatial variables relevant to managed fish species. This system applies to the OCS in Federal waters of the US Atlantic and Gulf of Mexico ≤ 50 m in depth.

The scheme is intended to meet the following criteria:

- It must be applicable over all US waters in the Atlantic and Gulf of Mexico.
- It must integrate with the CMECS. CMECS is a federally endorsed standard that also forms the framework for an associated BOEM product: the Marine Minerals Information System (MMIS). The Geoform and Substrate Components of CMECS are the most relevant ones in this case.
- It should be applicable at a variety of spatial scales.
- It should build on the best available science.
- Where possible, it should take into consideration the physical and chemical processes important to sand shoal formation, evolution, and temporal persistence.
- It should be conceptually open to updates as new science and data improve our knowledge.

A first step in the classification design process was a review of existing classification systems that might provide a framework or information relevant to this system. The following systems were reviewed:

- A Classification Scheme for Deep Seafloor Habitats (Greene et al. 1999)
- The CATAMI (Collaborative and Automated Tools for Analysis of Marine Imagery) Classification (Althaus et al. 2013)
- Seabed Geomorphology: A Two-Part Classification System (Dove et al. 2016)
- A Habitat Classification Scheme for the Long Island Sound Region (Auster et al. 2009)
- A New Classification Scheme of European Cold-Water Coral Habitats: Implications for Ecosystem-Based Management of the Deep Sea (Davies et al. 2017)
- A Geomorphic Classification of Estuaries and its Application to Coastal Resource Management – A New Zealand Example (Hume and Herdendorf 1988)
- INFOMAR Seabed Survey Seabed Habitat Classification (Thorsnes et al. 2018)
- A Habitat Classification Scheme for Seamount Landscapes: Assessing the Functional Role of Deep-Water Corals as Fish Habitat (Auster et al. 2005)
- Hierarchical Classifications of Sedimentary Architecture of Deep Marine Depositional Systems (Cullis et al. 2018)
- A Marine and Estuarine Habitat Classification System for Washington State (Dethier 1990)

Although some of these systems did reference geomorphological features, most included them as only as a descriptive part of a biological unit, or their focus was on a different geography than that of concern in this project. Three systems did address geomorphology and sand shoals directly (Auster et al. 2005; Dove et al. 2016; Greene et al. 1999), but only the following systems addressed the resources of interest in a systematic way, and they formed the source for most of the units:

- CMECS (FGDC (Federal Geographic Data Committee) 2012)
- Understanding the Habitat Value and Function of Shoals and Shoal Complexes to Fish and Fisheries on the Atlantic and Gulf of Mexico Outer Continental Shelf Literature Synthesis and Gap Analysis (Rutecki et al. 2014)
- Seafloor Geomorphology as Benthic Habitat (Harris and Baker 2012)

Given the breadth of the CMECS system, we decided to use it as a basis for the shoal classification scheme, and the other schemes were used in support of the method. We drew upon international subject matter experts (SMEs) to develop a framework for a classification scheme through consensus. Meetings with SMEs were scheduled to coincide with regional and international conferences, as well as facilitated webinars. In all cases, the participants were given a short presentation on the scope and objectives of the entire project and the need for a new classification scheme for sand features. The first meeting invited experts in the Southeast US region following a workshop on Improving Coordination in Seafloor Mapping in the Southeast US OCS in April 2018. Though regional in nature, this meeting drew upon geological models and knowledge for sand features off the Carolinas, Georgia, and Florida in the South Atlantic region. A meeting with international experts was scheduled around the GeoHab conference held in May 2018 in Santa Barbara, CA. For this meeting, our team focused on international standards for classifying sand features. Lastly, we hosted two facilitated webinars to gather additional comments on a draft scheme in June 2018 and concluded with a presentation and review among BOEM and US Army Corps of Engineers (USACE) staff in July 2018. From the totality of these meetings and calls, a structure for the classification scheme was developed.

3.2 Classification Scheme Structure

The sand shoal classification scheme draws from several elements of the CMECS and incorporates some new individual units from Rutecki et al.'s (2014) review. The CMECS classification system was used as the starting point in selecting appropriate variables and domains. CMECS was originally created through a collaboration between NatureServe, the NOAA, the US Environmental Protection Agency (US EPA), US Geological Survey (USGS), and the University of Rhode Island. This classification standard provides a method for categorizing the physical, biological, and chemical components of coastal and marine ecosystems. **Figure 3-1** shows the hierarchical nature of CMECS with new levels and modifiers relevant to this study proposed for an update to CMECS. **Table 3-1** presents the settings and components, including those suggested for inclusion in classifying shoal and related sand features. The following tables provide further details of the classification scheme components **(Table 3-2 to Table 3-6**). In the Appendix, we provide more detailed definitions for each class and modifier. Furthermore, the shoal classification scheme was applied using available data in the process described in Volume 4 of this report.

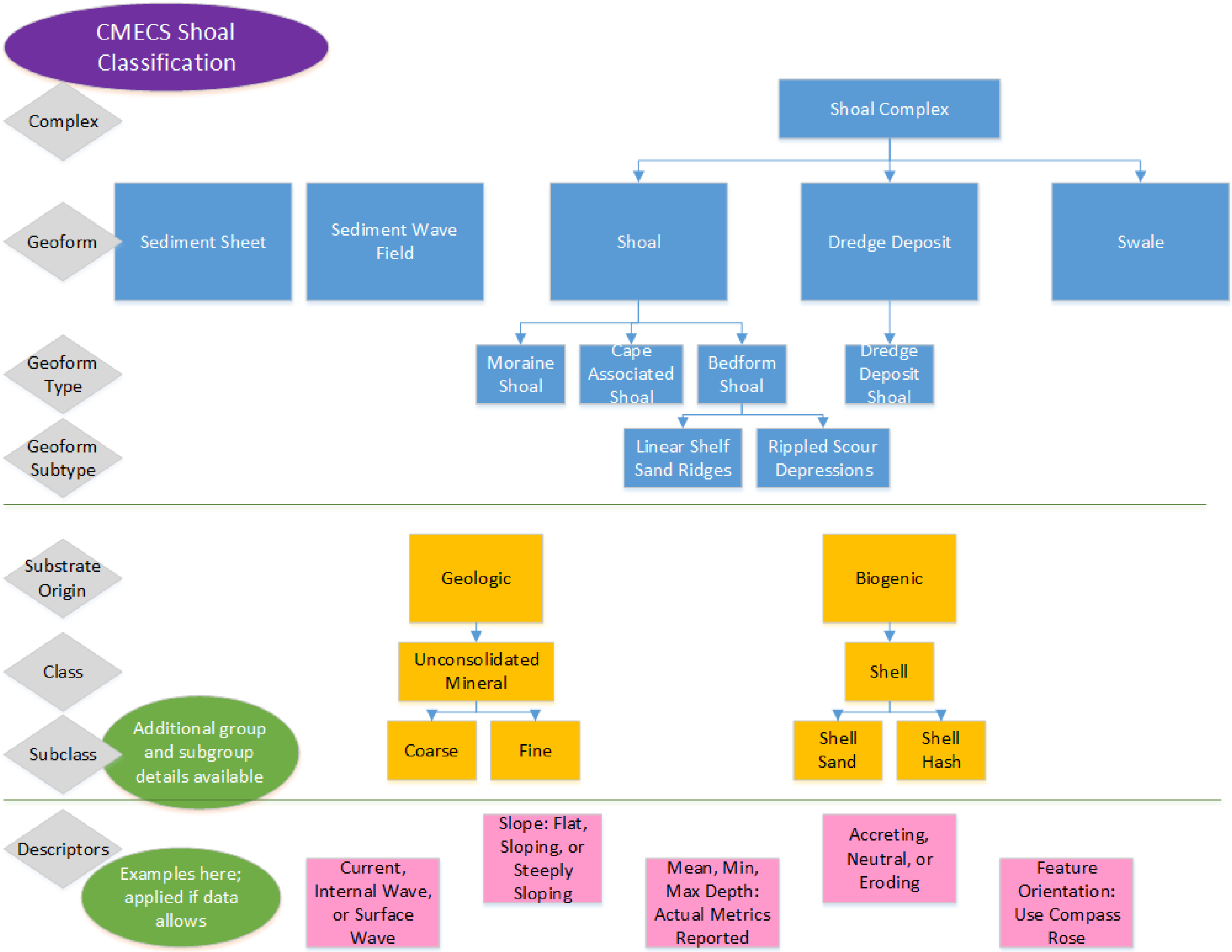


Figure 3-1. Hierarchical diagram of CMECS classification scheme proposed for sand features.

The following table illustrates the most basic structure of CMECS, which includes a series of settings, components, and modifiers. Indentation shows the hierarchical structure of items within each setting or component (**Table 3-1**). Items struck out in this classification scheme were not used in the ShoalMATE tool. Some variables in the ShoalMATE tool contain only a subset of original CMECS domains, which will be explained in further detail in subsequent tables. For the ShoalMATE tool, no distinction was made between Level 1 and Level 2 Geoforms, although due to the spatial resolution of input data layers, it is likely that most of these are Level 1. No information from the CMECS Aquatic Setting category was used in the ShoalMATE tool.

In **Table 3-2**, a subset of the available values from the CMECS ecoregion variable were used in the ShoalMATE tool. The Gulf of Mexico Fisheries Management Council (GMFMC) subdivided the Gulf of Mexico into a set of ecoregions that do not coincide with those from CMECS. These GMFMC-derived ecoregions were included in the ShoalMATE tool in a separate attribute for added spatial resolution and to match fish distribution descriptions in the GMFMC Fisheries Management Plan. For EcoregionFMC, entries may also be plural to include multiple ecoregions, such as “GMFMC Ecoregions 2-5.”

Table 3-2), the Salinity and Temperature Subcomponents are broken down into qualitative variables based on quantitative range descriptions. The ShoalMATE tool, however, includes quantitative range variables (min/max) as well as a variable for average temperature. This method ensures the highest level of precision for these values can be taken directly from source literature.

In **Table 3-3**, CMECS divides Geoform Components into Level 1 and Level 2. Level 1 Geoform components are generally larger than one square kilometer, while Level 2 are generally less than one square kilometer (see Federal Geographic Data Committee (FGDC) 2012, Section 6 for more details). However, the ShoalMATE tool does not make this distinction. A subset of the possible values were used for the CMECS variables Origin, Geoform, and GeoformType.

Table 3-4 shows the subset of CMECS Substrate Component used in the ShoalMATE tool in the native CMECS hierarchical structure.

In **Table 3-5**, the CMECS Biotic Setting and Biotic Class were selected for use in the ShoalMATE tool. Based on the level of detail in source documentation, it was determined that inclusion of the CMECS Biotic Subclass, Biotic Group, and Biotic Community were not necessary.

Lastly, in the variables are based on CMECS modifiers. In these cases, the CMECS modifiers were qualitative values based often on quantitative ranges, while the final variables selected for the ShoalMATE tool remained quantitative and captured varying ranges.

Table 3-1. CMECS settings and components.

Also see Table 2.1 in Federal Geographic Data Subcommittee (2012). Modifiers may be applied to one or more components. See Federal Geographic Data Subcommittee 2012 for further details.

Biogeographic Setting (BS)	Aquatic Setting (AS)	Water Column Component (WC)	Geoform Component (GC)	Substrate Component (SC)	Biotic Component (BC)
~~Realm~~ *~~Province~~* *Ecoregion*	*~~System~~* *~~Subsystem~~* *~~Tidal Zone~~*	~~Layer Subcomponent~~ Salinity Subcomponent Temperature Subcomponent ~~Hydroform Subcomponent~~ *~~Hydroform Class~~* *~~Hydroform~~* *~~Hydroform Type~~* ~~Beiogeochemical Feature Subcomponent~~	~~Tectonic Setting Subcomponent~~ ~~Physiographic Setting Subcomponent~~ Level 1 Geoform Subcomponent *Geoform Origin* *Level 1 Geoform* *Level 1 Geoform Type* Level 2 Geoform Subcomponent *Geoform Origin* *Level 2 Geoform* *Level 2 Geoform Type*	*Substrate Origin* *Substrate Class* *Substrate Subclass* *Substrate Group* *Substrate Subgroup*	*Biotic Setting* *~~Biotic Class~~* *~~Biotic Subclass~~* *~~Biotic Group~~* *~~Biotic Community~~*

Table 3-2. Biogeographic Setting.

Ecoregion	EcoregionFMC*
Scotian Shelf	GMFMC Ecoregion 1
Gulf of Maine/Bay of Fundy	GMFMC Ecoregion 2
Virginian	GMFMC Ecoregion 3
Carolinian	GMFMC Ecoregion 4
Northern Gulf of Mexico	GMFMC Ecoregion 5
Floridian	

Table 3-2. Water Column Component.

ShoalMATE tool Water Column Component Variables:
TempMin
TempMax
TempAvg
SalinityMin
SalinityMax

Table 3-3. Geoform Component.

Geoform Component Origin (GC Origin)	Geoform Component Geoform (GC Geoform)	Geoform Component Type (GC Type)
Geologic	Shoal	Moraine Shoal
		Cape-Associated Shoal (CMECS provisional unit)
		Bedform Shoal (CMECS provisional unit)
		Isolated Shelf Shoals (CMECS provisional unit)
	Dredge Deposit	Dredge Deposit Shoal
	Swale	-
	Sediment Wave Field	-
	Sediment Sheet	-
	Flat	Tidal Flat

Table 3-4. Substrate Component.

Substrate Component Origin (SC Origin)	Substrate Component Class (SC Class)	Substrate Component Subclass (SC Subclass)	Substrate Component Group (SC Group)	Substrate Component SubGroup (SC Subgroup)
Geologic Substrate	Unconsolidated Mineral Substrate	Coarse Unconsolidated Substrate	Gravel	Boulder
				Cobble
				Pebble
				Granule
			Gravel Mixes	Sandy Gravel
				Muddy Sandy Gravel
				Muddy Gravel
			Gravelly	Gravelly Sand
				Gravelly Muddy Sand
				Gravelly Mud
		Fine Unconsolidated Substrate	Slightly Gravelly	Slightly Gravelly Sand
				Slightly Gravelly Muddy Sand
				Slightly Gravelly Sandy Mud
				Slightly Gravelly Mud
			Sand	Very Coarse Sand
				Coarse Sand
				Medium Sand
				Fine Sand
				Very Fine Sand
			Muddy Sand	Silty Sand
				Silty-Clayey Sand
				Clayey Sand
			Sandy Mud	Sandy Silt
				Sandy Silt-Clay
				Sandy Clay
			Mud	Silt
				Silt-Clay
				Clay
Biogenic Substrate	Shell Substrate	Shell Hash	Clam Hash	*Coquina* Hash
			Crepidula Hash	-
			Mussel Hash	-
			Oyster Hash	-
		Shell Sand	Clam Sand	*Coquina* Sand

Table 3-5. Biotic Component.

Biotic Component Setting (BCSetting)	Biotic Component Class (BCClass)
Planktonic	Zooplankton
	Floating/Suspended Plants and Macroalgae
	Phytoplankton
	Floating/Suspended Microbes
Benthic/Attached	Reef Biota
	Faunal Bed
	Microbial Communities
	Aquatic Vegetation Bed
	Emergent Wetland
	Scrub-Shrub Wetland

Table 3-6. Modifiers.

ShoalMATE tool Variable Name	ShoalMATE tool Variable Description	Original CMECS Variable Name	Original CMECS Variable Description
Grain Size (Phi)	Sediment grain size in Phi (numerical)	Seafloor Rugosity	Qualitative descriptors based on ranges of grain size
DOmin	Minimum dissolved oxygen (mg/L) at which a fish species or life stage can survive, or minimum dissolved oxygen measured over a sand resource	Oxygen	Qualitative descriptors based on ranges of dissolved oxygen values
DOmax	Maximum dissolved oxygen (mg/L) at which a fish species or life stage can survive, or maximum dissolved oxygen measured over a sand resource		
DepthMin_m	Minimum depth (m) at which a fish species or life stage can be found, or the minimum measured depth of a sand resource (not calculated during storm events)	Benthic Depth Zones	Qualitative descriptors based on depth ranges (m)
DepthMax_m	Maximum depth (m) at which a fish species or life stage can be found, or the maximum measured depth of a sand resource (not calculated during storm events)		
ChlaMin	Minimum chlorophyll a (µg/L) at which a fish species or life stage can survive, or the minimum measured chlorophyll a (µg/L) measured over a sand resource	Phytoplankton Productivity	Qualitative descriptors based on a range of chlorophyll a (µg/L)
ChlaMax	Maximum chlorophyll a (µg/L) at which a fish species or life stage can survive, or the maximum measured chlorophyll a (µg/L) measured over a sand resource		
TurbMin	Minimum turbidity at which a fish species or life stage can survive, or the minimum turbidity measured on a sand resource	Turbidity	Qualitative descriptors based on a range of turbidity values measured in Secchi depths
TurbMax	Maximum turbidity at which a fish species or life stage can survive, or the maximum turbidity measured on a sand resource		
SubstrateDesc	A subset of the associated CMECS variable (see right). Allowed values: Carbonate, Compacted, Mobile, Non-Mobile, Patchy, Siliciclastic, Sulfidic, Volcaniclastic, Volcanic Ash, Well-Mixed, Heterogenous (CMECS provisional unit)	Substrate Descriptors	Qualitative descriptors of seafloor substrate

3.3 Applying the Classification Scheme

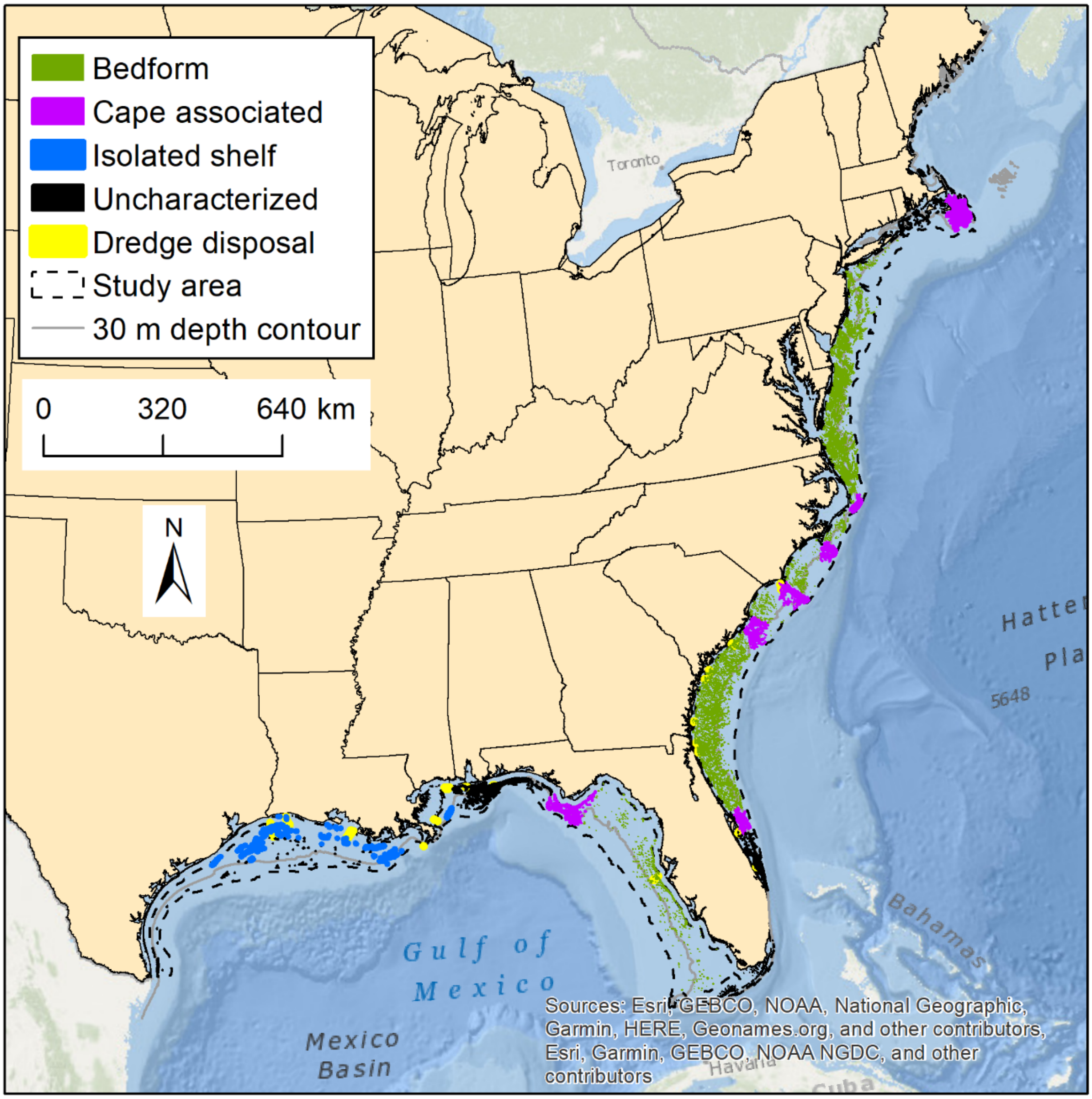
The process of classifying the delineated shoals into scheme units builds on the characteristics described in **Section 2.3**, which covers the identification of the shoal. Rutecki et al. (2014) includes discussion of the environmental drivers that influence sand distribution and movement on the OCS. They also convey a number of shoal geoform types that have been integrated into this classification system as provisional CMECS units. Beyond the identification of shoal geoform types and their definitions, Rutecki et al. (2014) also provides specific examples of each geoform type in the Atlantic and Gulf of Mexico. In this section, we focus on classifying the shoal features into geoforms defined above.

Individual shoals were often grouped in space, especially in proximity to offshore capes. Groups of shoals are refered to as "complexes," which contain two or more shoals with intermingling troughs or swales. The shoal complex are connected by past or present sedimentary and hydrodynamic processes (Rutecki et al. 2014). To assign individual shoals and swales into "shoal complexes," we applied Tobler's first law of geography (Tobler 1970), "everything is related to everything else, but near things are more related than distant things." Specifically, we grouped all shoals/swales that were within 2.5 km of each other. Initially, we tested the aggregation of shoals/swales with distances ranging from 0.5–5 km. We selected a distance of 2.5 km because shorter distances led to multiple shoal complexes identified within singular, cape-associated shoal areas with the same geological origins. Meanwhile, distances ≥ 3 km led to cape-associated shoals clumped together with sand shoals with different geological origins (e.g., cape-associated and bedform shoals).

The labelling of shoals and complexes by geoform type is inevitably an interpretive process relying on a mix of localized studies, geographic position, and context, as well as other quantitative and qualitative criteria. These criteria can be referred to by the term "classifiers," which are characteristics of individual shoals that are necessary to assign them to specific categories. For example, dominant tree height would be a classifier that allows one to distinguish between forest and shrub land. The geoform type definitions and specific geographic examples of each shoal type from Rutecki et al. (2014) formed a basis for the qualitative classification of the mapped shoals into the various categories. Specific classifiers applied in this process include:

- Proximity to coastal landforms such as capes, inlets, deltas, and historical deltas
- Shape and orientation
- Proximity and spatial relationship to nearby similar shoals
- Proximity to shoals that were classified into geoform types in Rutecki et al. (2014) and associated studies
- Position on the OCS (coastal or offshore)
- Spatial continuity with terrestrial ridge-like features

Evaluation of these factors, consideration of the quantitative bathymetric parameters, and prior characterization by other researchers was used to arrive at the final classified shoal data layer employed in ShoalMATE and presented in the following maps (**Figure 3-2** to **Figure 3-5**). Cape-associated shoals are distributed as their name indicates with prominent landward capes along the Atlantic and to lesser extent Gulf of Mexico (**Figure 3-2**). Isolated shelf shoals are the most dominant in the Gulf of Mexico (**Figure 3-3**), whereas bedform shoal features dominate the features on the Atlantic Coast (**Figure 3-4** and **Figure 3-5**).



Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors, Esri, Garmin, GEBCO, NOAA NGDC, and other contributors

Figure 3-2. Classified sand features throughout the study area in the Gulf of Mexico and Atlantic OCS.

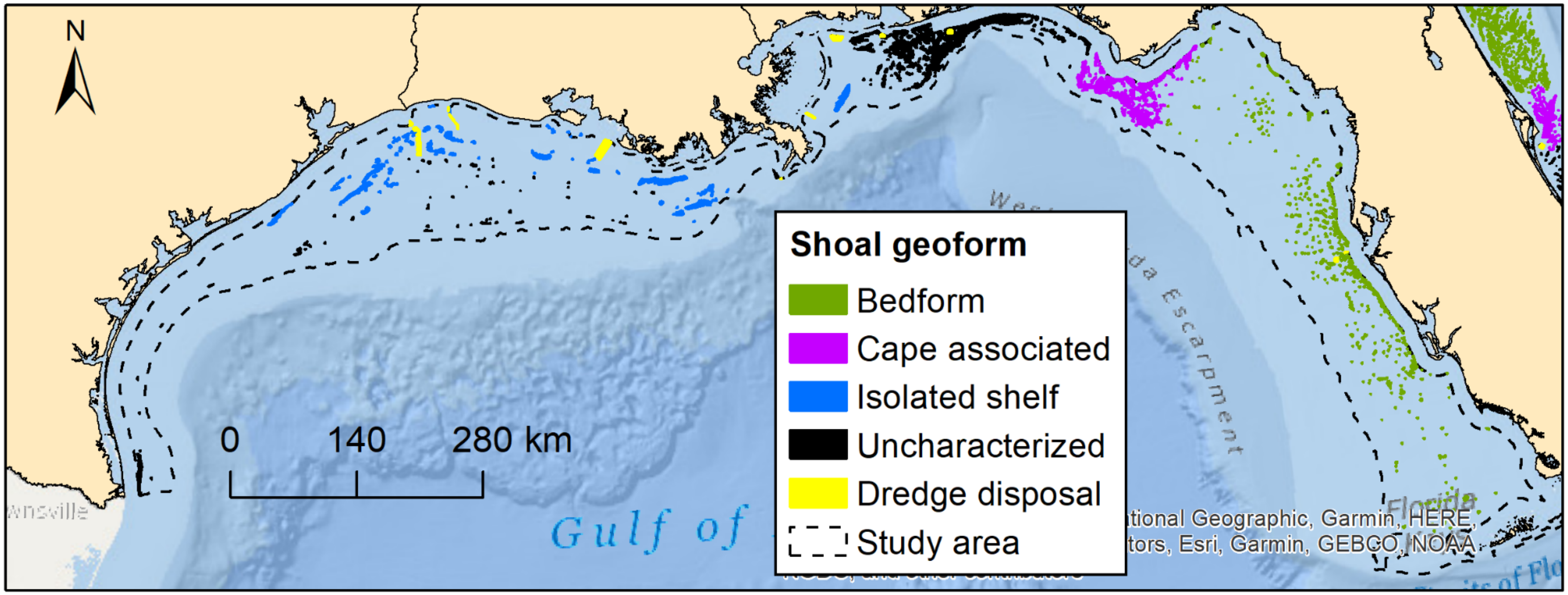
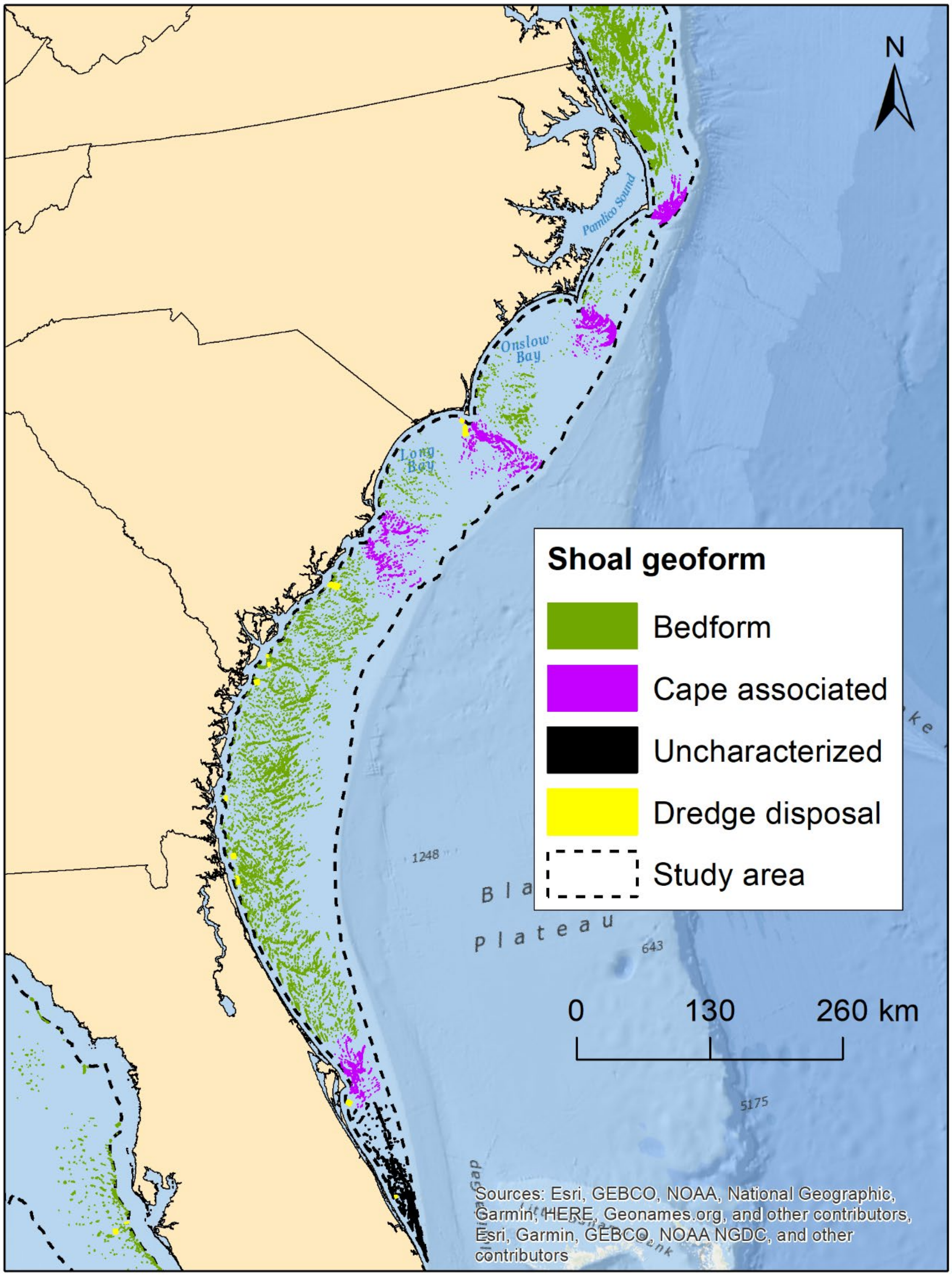


Figure 3-3. Overview map of classified shoal distributions in the northern Gulf of Mexico region.



Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors, Esri, Garmin, GEBCO, NOAA NGDC, and other contributors

Figure 3-4. Overview map of classified shoals along the southeast coast of the US.

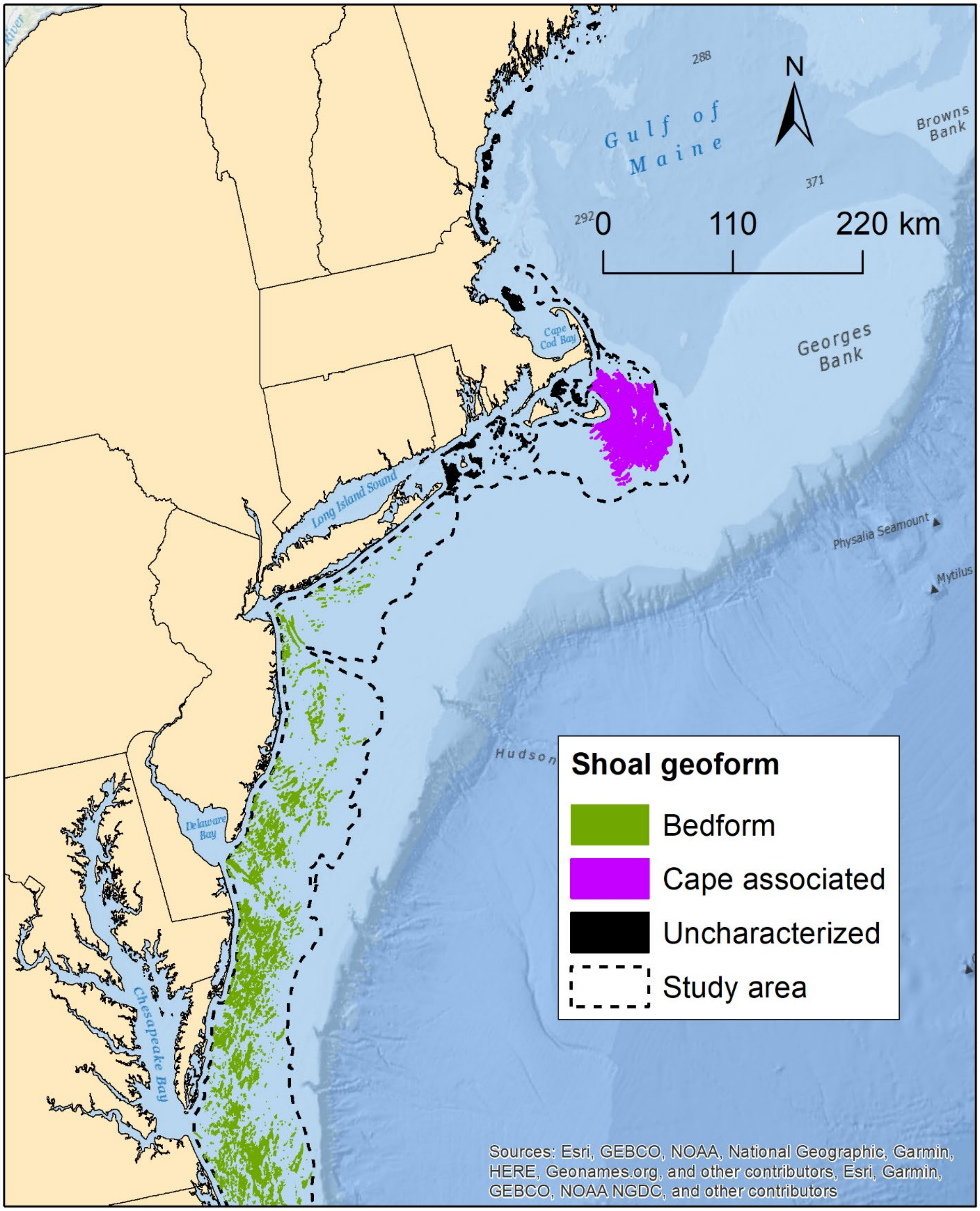


Figure 3-5. Overview map of classified shoal distributions in the US mid-Atlantic and New England region.

3.4 Verifying the Shoal and Shoal Complex Dataset

Before integrating the classified shoals dataset into the ShoalMATE tool, we assessed the accuracy of the results. We did not have the capability to collect new high-resolution geophysical or geotechnical data to quantitatively validate our modeled distribution of sand shoals. Instead, we conducted a qualitative assessment by comparing classified shoals to shoal features commonly known and mapped as "shoals" or similar features. More specifically, our classifications were compared to two reference place-name datasets to see how well the product characterized named shoals and shoal-like features.

1. *Marine Place Names* - 2016. These data are derived from features on the NOAA Electronic Navigational Charts and contain names for features in the US territorial waters and the OCS. Because different place names are displayed depending on the scale displayed, we used a 1:80,000 scale. The dataset had a total of 55 categories of features, and we used the following categories for spatial comparison with our results: a) bank, b) bar, c) ridge, d) shoal
2. *Undersea Feature Names* - 2017. The GEOnet Names Server (GNS) provides access to the National Geospatial Intelligence Agency's (NGA) and the US Board on Geographic Names' (BGN) database of geographic feature names. The database is the official repository of foreign place-name decisions approved by the BGN. Geographic coordinates are approximate and are intended for general location. Place-name information is based on the Geographic Names Database, which contains official standard names approved by the United States Board on Geographic Names and maintained by the National Geospatial-Intelligence Agency. A total of 55 types of features were present in this dataset. The following were extracted for the comparison: a) undersea bank and banks, b) undersea ridge and ridges, c) undersea shoal and shoals.

The source datasets have point topology and consist of the centroids of what become textual labels on Electronic Navigation Charts or other cartographic products. These labels are intended to loosely characterize the extent and orientation of the features on a map. To avoid false negatives where the textual label may have intersected the shoal dataset but the centroid did not, the centroid points were buffered to a 3-km radius. Both datasets include features in both state and Federal waters. Buffered features that fell outside that zone were removed because the area of interest pertains to Federal waters less than 50 m in depth and because we restricted our classification shoreward of the continental shelf break beginning at 40 m.

Overall the shoals dataset strongly aligns with named shoals and shoal-like features as compared with two nationally scoped datasets. Named shoals in these source data tended to be located in nearshore waters. This is probably a function of their role as a navigation hazard and ease of observation. Many of the named shoals in Federal waters were located near Nantucket, RI, so there is some geographical bias inherent in these results. Nonetheless, the results suggest that the derived shoal maps are accurately capturing these features and should be suitable for its purpose as a screening tool to identify other possible sand resources. Many of the largest sand features delineated corresponded well to verified sand resources. It is important to note that these classified features are predictions; those features not already named or verified as sand resources by BOEM and other agencies need further validation and high-resolution seafloor surveys.

The Marine Place Name database included the feature type "bars" that exclusively fell within state waters shoreward of the boundary for our study area, and ridges occurred at depths beyond 50 m or outside the Atlantic and Gulf of Mexico. The vast majority of named shoals also were identified in state waters, outside our area of study. The results showed a user's accuracy (percent of named shoals present in the dataset) of 95% for shoal-like features (**Table 3-7**). An assessment of the producer's accuracy (how many of the mapped shoals have been mapped correctly) is not possible without a separate validation process.

The Undersea Feature Place Names database included a much smaller number of shoal-like features in the source data. This is likely a function of the offshore focus of this database. Fewer banks were present overall, but a strong percentage were located in the study area. Few ridges occurred in the database and in the study area as well. Those shoals that were present were accurately identified in the derived shoal maps (**Table 3-7**). The results showed a user's accuracy (percent of named shoals present in the dataset) of 88% for shoals and an aggregate accuracy of 57% for shoal-like features. As with the Marine Place Names data, a producer's accuracy is not possible at this time.

Table 3-7. Spatial alignment of detected shoal features with named places for "Marine Place Name" (Top) and "Undersea Feature Place Name" (Bottom) datasets.

Marine Place Name Feature Type	Number of Features in Source Data	Number of Features within Study Area	Number of Features Intersecting with Shoal Dataset
Bars	63	0	0
Ridges	30	0	0
Shoals	761	46	44
Undersea Feature Type	**Number of Features in Source Data**	**Number of Features within Study Area**	**Number of Features Intersecting with Shoal Dataset**
Banks	21	6	3
Ridges	7	1	1
Shoals	15	9	8

Our analysis of a large-scale coastal relief digital elevation model was limited by the quality and coverage in the dataset. The CRM is a compilation of soundings from current and modern hydrographic sonar survey, as well as historical and sometimes sparse soundings, smoothed to a consistent 90-m resolution through interpolation or modeling. The aggregation of data across time does ignore the temporal dynamics and movement of sediment along the Gulf and Atlantic Coasts and may only represent larger features or shoal complexes that are relatively persistent as features, even if their exact position may change over time with sediment transport (Pendleton et al. 2017). The classified collection of shoal complexes should be applied as an initial screening tool for planning modern surveys that would be required to locate the amount and shape of sand resources available. Our analysis restricted feature sizes to ≥ 5 ha in the Atlantic based upon prior reviews of significant sand resources (Rutecki et al. 2014), and we were further limited to identifying features of > 20 ha in the Gulf of Mexico. One of the major challenges in our analysis was detecting and delineating relatively low-relief and small bedform sand features, as are present off the coast of North Carolina, South Carolina, Georgia, and the western Gulf Coast of Florida. The relative importance of these features as sand resources and fish habitat need to be further explored.

A second step in evaluating the quality of the shoal dataset was a visual comparison to known sand resources. Classified shoals aligned well with verified sand resources identified by BOEM and its partners. In the Gulf of Mexico (**Figure 3-6**), Ship Shoal was identified as an isolated shelf shoal, though the shape of the polygon from the classification model deviates from the boundary of the sand resource. This is likely because sand resource mapping included both shoal and non-shoal sediment resources. Similarly, verified sand resources aligned well with the bedform shoals delineated off the northern Outer Banks of North Carolina (**Figure 3-7**), though the model classifies additional similarly shaped shore parallel sand features in the region. Differences in the shapes and extent between physically mapped sand resources and the classified layer could be due to the knowledge of the subsurface sand depth, resolution of the source data, or an artifact of temporal dynamics of the shoals. Verified sand resources have been surveyed using modern hydrographic techniques and higher resolution (meters to tens of meters) surfaces. The delineation of our classified layer was made from a composite CRM, which may include another temporal image of the shoal that may have shifted or changed in morphology due to sediment transport and coastal circulation dynamics. Similarly, bedform shoals were delineated and conform to identified sand resources off Virginia and Delaware, though once again, there are numerous sand features classified by the model, with many farther offshore that have not yet been verified as sand resources by BOEM and others (**Figure 3-8**).

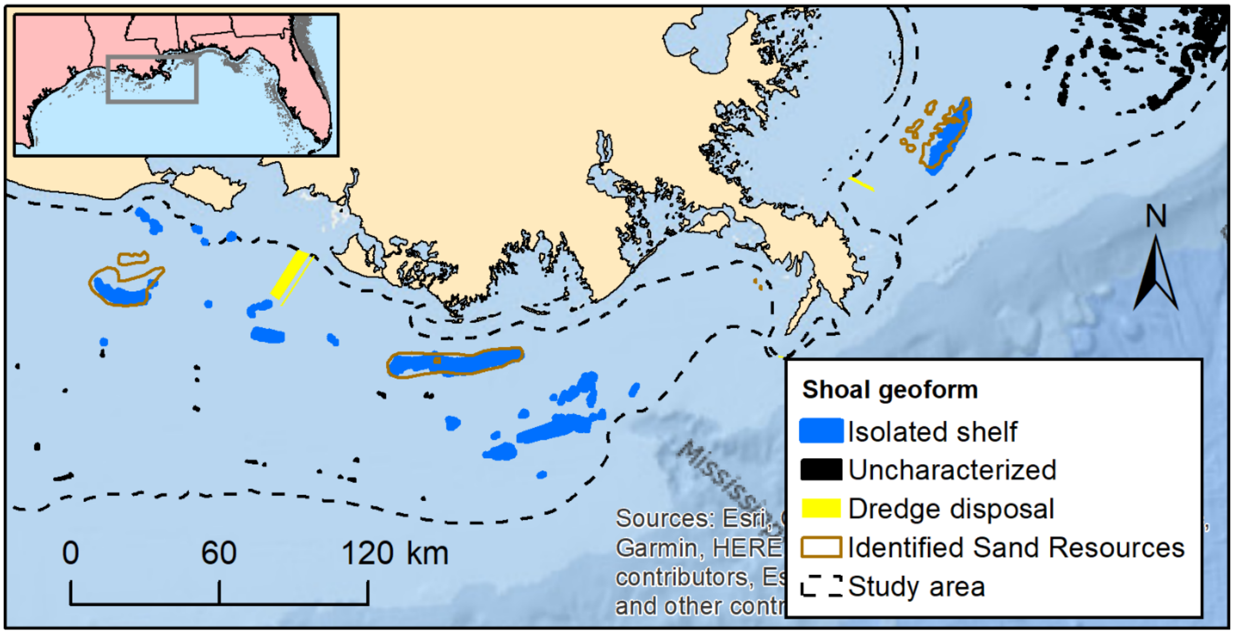


Figure 3-6. Concordance of classified shoals with known and identified sand resources (tan polygons) south of Louisiana in the Gulf of Mexico region.

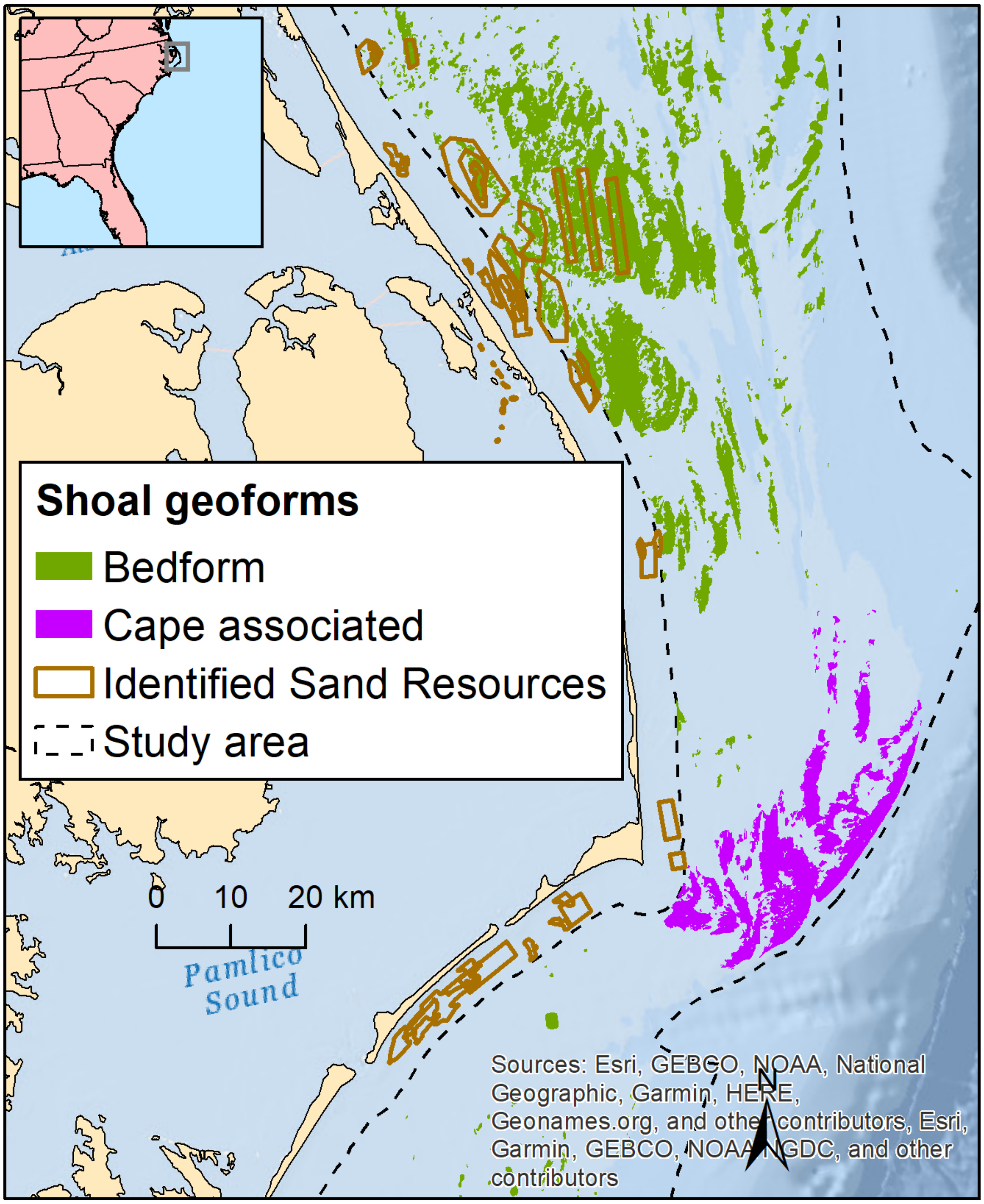


Figure 3-7. Concordance of classified shoals with identified sand resources (tan polygons) off Cape Hatteras in the South Atlantic region.
Note identified sand resource area also shown shoreward of the state boundary outside the study area.

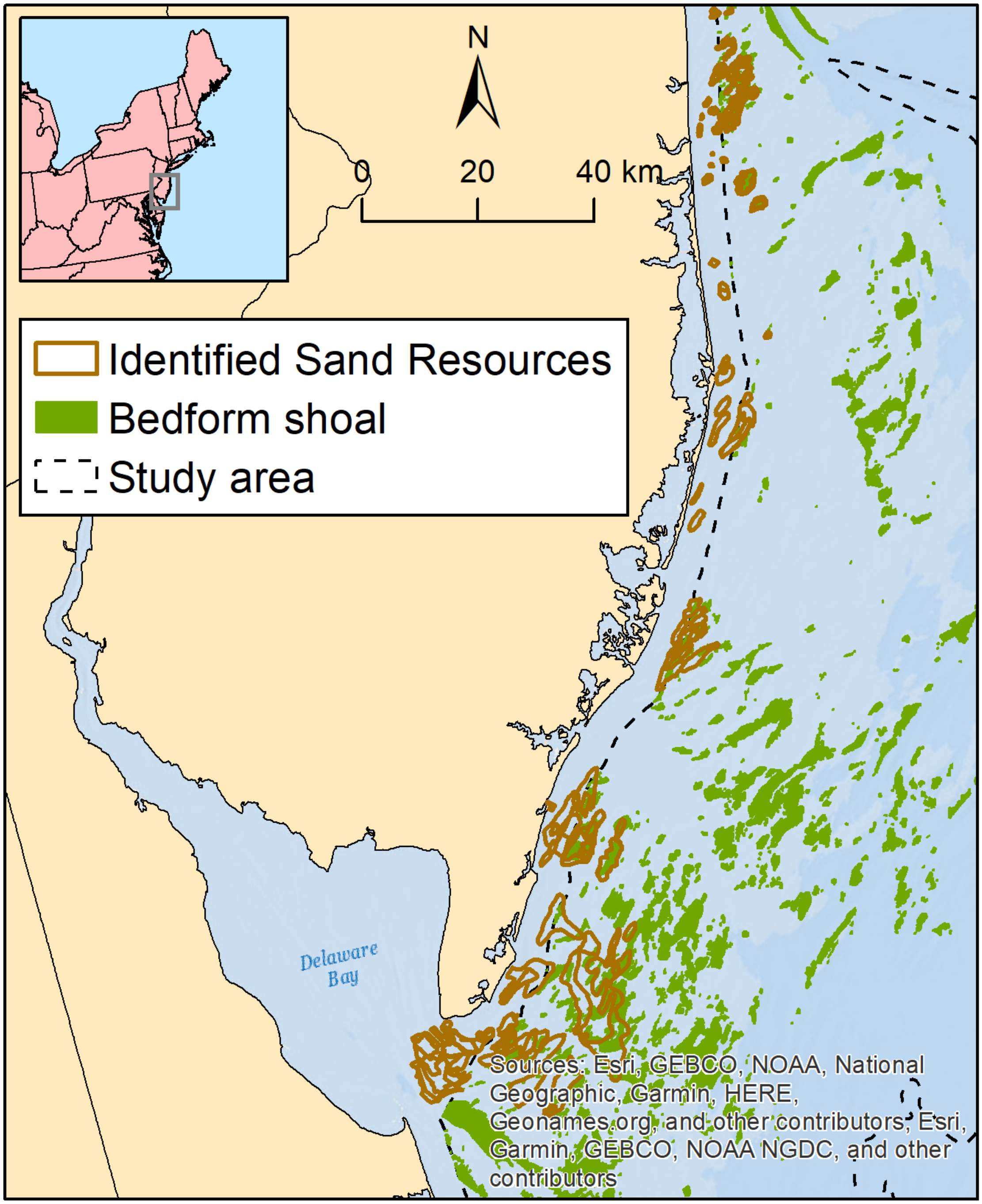


Figure 3-8. Concordance of classified shoals with verified sand resources (tan polygons) in the mid-Atlantic region.

Note identified sand resource area also shown shoreward of the state boundary outside the study area.

Improvements to this classification model and derived layers could come in several forms. First, our exercise focused exclusively on a study area bounded by Federal management jurisdictions and excluded waters under state management jurisdiction. Although the overall framework and modeling approach could be extended to include state waters, several important factors may complicate the modeling process, including increased variation and noise in nearshore BPI and slope values, as well as the reduced usefulness of factors like distance to shore and depth. A separate model derivation would be required to extend classifications to these areas. It is not likely that dredging efforts would extend beyond the 50-m depth contour, so extensions offshore may not be necessary. Secondly, we did not include sediment type into the shoal and sand feature classifications. Sediment and bedform maps exist for both the Gulf and Atlantic Coasts elsewhere, developed through separate initiatives (e.g., TNC's South Atlantic Bight Marine Assessment (Conley et al. 2017), Chris Jenkins, University of Colorado, unpublished data). These maps were modeled using various spatial interpolation techniques from compilation of historical to modern bottom samples. In all cases, these classifications should be taken as screening tools and will require modern geological surveys and validation.

4 Results and Discussion

This study builds upon previous syntheses of the dynamics and distribution of offshore sand features in the Gulf of Mexico and US Atlantic continental shelf (Rutecki et al. 2014). Prior shoal classification studies have focused on discrete areas, such as cape-associated shoals along coastal North Carolina (Thieler et al. 2014) or shoal complexes near southwest Florida in the Gulf of Mexico (Finkl et al. 2007). The classification conducted here extends the concept that seafloor geomorphology and complexity metrics derived from broad-scale coastal elevation models can be used as an initial survey of broad areas of the continental shelf to delineate shoals and shoal complexes (Knorr 2017). Previously, a classification model of the east coast of Florida used 10-m resolution seafloor imagery to detect shoals and similar sand features (Knorr 2017) and found that simple thresholds of complexity metrics like rugosity can be used to delineate sand features. In contrast to Knorr (2017), we used a broader extent and a coarser 90-m data resolution to analyze seafloor geomorphology and complexity metrics to delineate features and classify shoals. Our results showed seafloor complexity metrics were still distinct from the surrounding seafloor at this 90-m resolution. Seafloor metrics, such as slope and the BPI, were substantially higher than the surrounding seafloor across all three geographies analyzed here (**Table 2-1**). Our study also differed from Knorr (2017) in that we used the BPI and distance from shore as predictors. Large shoals and shoal complexes were readily visible in the bathymetry surfaces, and these were delineated using a range of spatial scales of the BPI, depending upon the geographic area. For the Gulf of Mexico in particular, the larger scale of BPI (71 x 71 cells) was helpful to delineate wide (> 3 km) shoals that were partially characterized by low slope (i.e., flat cells) within 90-m resolution cells. Distance to shoreline was helpful in the classification because shoals are distinguished as shallow areas that are farther offshore than other waters of similar depths. The unsupervised classification accounts for such predictor combinations, although such interactions are difficult to quantify in descriptive statistics.

In the Gulf of Mexico, large cape-associated and isolated shelf shoals were the most prominent sand features detected and classified (**Figure 3-3)**, specifically Ship Shoal, Trinity Shoal, Sabine Bank, and St. Bernard Shoals near Louisiana and the cape shoals near Apalachicola, FL. There were other classified shoals scattered along Texas, Louisiana, and Alabama that were left as uncharacterized sand feature classes. Similarly, the majority of the west Florida shelf was populated by smaller features that have been previously identified as valuable sand sources for beach nourishment in the region (Finkl et al. 2007). Cape-associated shoals are readily visible in the base bathymetry maps and easily delineated in our models in the US South Atlantic (**Figure 3-4**). These shoals are associated with dynamic seabed areas off Cape Canaveral, FL, and along the Carolinas and Virginia Coasts. However, the majority of areas of potential sand resources appear to be captured in the scattered and smaller bedform features off South Carolina and Georgia (**Figure 3-4**). The small size and relatively low relief of these features may result in uncertainty in size, number, and extent in this region. North of Cape Hatteras into the mid-Atlantic and

New England, smaller bedforms dominate except around Cape Cod where cape-associated shoals are present (**Figure 3-5**).

We labeled shoal complexes by their geoform whenever possible with a basis from Rutecki et al.'s (2014) classification based on geological origin. More specifically, we classified geoform types into: 1) cape-associated shoals, 2) bedform shoals, 3) isolated shelf shoals, 4) dredge disposal sites, and 5) uncharacterized shoals. To name shoals, we examined labels from the ESRI oceans basemap, literature sources, and examples from the Rutecki et al. (2014) review of sand shoals. Dredge disposal sites were identified from disposal locations that were categorized as dredged material disposal or spoil grounds (U.S. Environmental Protection Agency n.d.).

5 Literature Cited

Althaus F, Hill N, Edwards L, Ferrari R, Case M, Colquhoun J, Edgar G, Fromont J, Gershwin L, Gowlett-Holmes K. 2013. CATAMI Classification Scheme for scoring marine biota and substrata in underwater imagery—A pictorial guide to the Collaborative and Annotation Tools for Analysis of Marine Imagery and Video (CATAMI) classification scheme. Version 13.

Auster PJ, Heinonen KB, Witharana C, McKee M. 2009. A habitat classification scheme for the Long Island Sound region. Long Island Sound Study Technical Report. EPA Long Island Sound Office, Stamford, Connecticut. 06904. 83 pp.

Auster PJ, Moore J, Heinonen KB, Watling L. 2005. A habitat classification scheme for seamount landscapes: assessing the functional role of deep-water corals as fish habitat. In Cold-water corals and ecosystems. Berlin, Heidelberg: Springer. 761-769 pp.

Charlier RH, Charlier CC. 1992. Environmental, economic, and social aspects of marine aggregates' exploitation. Environmental Conservation. 19(1):29-38.

Conley MF, Anderson MG, Steinberg N, Barnett A. 2017. The South Atlantic Bight marine assessment: species, habitats and ecosystems. The Nature Conservancy, Eastern Conservation Science.

Cullis S, Colombera L, Patacci M, McCaffrey WD. 2018. Hierarchical classifications of the sedimentary architecture of deep-marine depositional systems. Earth-Science Reviews. 179:38-71.

Davies J, Guillaumont B, Tempera F, Vertino A, Beuck L, Ólafsdóttir S, Smith C, Fosså J, Van den Beld I, Savini A. 2017. A new classification scheme of European cold-water coral habitats: implications for ecosystem-based management of the deep sea. Deep Sea Research Part II: Topical Studies in Oceanography. 145:102-109.

de Jong MF, Baptist MJ, van Hal R, de Boois IJ, Lindeboom HJ, Hoekstra P. 2014. Impact on demersal fish of a large-scale and deep sand extraction site with ecosystem-based landscaped sandbars. Estuarine, Coastal, and Shelf Science. 146:83-94.

Dethier M. 1990. A marine and estuarine habitat classification system for Washington State. Washington Natural Heritage Program, Dept. Natural Resources.

Dove D, Bradwell T, Carter G, Cotterill C, Gafeira Goncalves J, Green S, Krabbendam M, Mellett C, Stevenson A, Stewart H. 2016. Seabed geomorphology: a two-part classification system. British Geological Survey, Marine Geoscience Programme. Open report OR/16/001.

Drucker BS, Waskes W, Byrnes MR. 2004. The US Minerals Management Service Outer Continental Shelf sand and gravel program: environmental studies to assess the potential effects of offshore dredging operations in federal waters. Journal of Coastal Research 20(1):1-5.

FGDC (Federal Geographic Data Committee). 2012. Marine and Coastal Spatial Data Subcommittee. FGDC-STD-018-2012. Coastal and Marine Ecological Classification Standard. Reston (VA): Federal Geographic Data Committee.

Finkl CW, Benedet L, Andrews JL, Suthard B, Locker SD. 2007. Sediment ridges on the west Florida inner continental shelf: sand resources for beach nourishment. Journal of Coastal Research. 231: 143-159.

Greene HG, Yoklavich MM, Starr RM, O'Connell VM, Wakefield WW, Sullivan DE, McRea JE, Cailliet GM. 1999. A classification scheme for deep seafloor habitats. Oceanologica Acta. 22(6):663-678.

Harris PT, Baker EK. 2012. Why map benthic habitats? Seafloor geomorphology as benthic habitat. Elsevier. 3-22 pp.

Hume TM, Herdendorf CE. 1988. A geomorphic classification of estuaries and its application to coastal resource management—a New Zealand example. Ocean and Shoreline Management. 11(3):249-274.

Kim TG, Grigalunas TA, Han K-N. 2008. The economic costs to fisheries because of marine sand mining in Ongjin Korea: concepts, methods, and illustrative results. Ecological Economics. 65(3):498-507.

Knorr PO. 2017. Searching for sand in Florida: exploiting sea floor morphology as a reconnaissance tool. Shore & Beach. 85(3):1.

La Porta B, Targusi M, Lattanzi L, La Valle P, Paganelli D, Nicoletti L. 2009. Relict sand dredging for beach nourishment in the central Tyrrhenian Sea (Italy): effects on benthic assemblages. Marine Ecology. 30:97-104.

Nairn R, Johnson JA, Hardin D, Michel J. 2004. A biological and physical monitoring program to evaluate long-term impacts from sand dredging operations in the United States Outer Continental Shelf. Journal of Coastal Research. 20(1):126-137.

NOAA National Ocean Service, Office for Coastal Management. 2016. Outer Continental Shelf Lands Act. Charleston (SC): NOAA's National Ocean Service, Office for Coastal Management. [accessed 2 March 2018] https://www.marinecadastre.gov/data/.

NOAA National Centers for Environmental Information. 2010. U.S. Coastal Relief Model. [accessed 2 March 2018]. http://www.ngdc.noaa.gov/mgg/coastal/crm.html.

NOAA National Centers for Environmental Information. 2016. Bathymetric data viewer. [accessed 15 May 2018]. https://maps.ngdc.noaa.gov/viewers/bathymetry/.

NOS (National Ocean Service). 2008. National Ocean Service, Office of Coast Survey, US Bathymetric & Fishing Maps. [accessed 2008]. http://www.ngdc.noaa.gov/mgg/bathymetry.

Pendleton EA, Brothers LL, Thieler ER, Sweeney EM. 2017. Sand ridge morphology and bedform migration patterns derived from bathymetry and backscatter on the inner-continental shelf offshore of Assateague Island, USA. Continental Shelf Research. 144:80-97.

Robbins LL, Hansen ME, Raabe EA, Knorr PO, Browne J. 2007. Cartographic production for the Florida Shelf Habitat (FLaSH) Map Study: generation of surface grids, contours, and KMZ files. St Petersburg (FL): U.S. Geological Survey, Open-File Report 2007-1397. 11 pp.

Rutecki D, Dellapenna T, Nestler E, Scharf F, Rooker J, Glass C, Pembroke A. 2014. Understanding the habitat value and function of shoals and shoal complexes to fish and fisheries on the Atlantic and Gulf of Mexico outer continental shelf. Literature synthesis and gap analysis. Herndon (VA): U.S. Department of the Interior, Bureau of Ocean Energy Management. Contract # M12PS00009. BOEM 2015-012. 176 pp.

Thieler ER, Foster DS, Himmelstoss EA, Mallinson DJ. 2014. Geologic framework of the northern North Carolina, USA inner continental shelf and its influence on coastal evolution. Marine Geology. 348:113-130.

Thorsnes T, Bjarnadóttir LR, Jarna A, Baeten N, Scott G, Guinan J, Monteys X, Dove D, Green S, Gafeira J, et al. 2018. National Programmes: Geomorphological mapping at multiple scales for multiple purposes. In: Micallef A, Krastel S, Savini A, editors. Submarine Geomorphology. Cham: Springer International Publishing. 535-552 pp.

Tobler WR. 1970. A computer movie simulating urban growth in the Detroit region. Economic Geography. 46(sup1):234-240.

U.S. Environmental Protection Agency. n.d. Ocean Dredged Material Disposal Sites (ODMDS) in the Southeast: Ocean Dumping In The Southeast. GSAA Coasta & Ocean Portal; [accessed 2018 9 April]. http://gsaaportal.org/explore/catalog.

Vasslides JM, Able KW. 2008. Importance of shoreface sand ridges as habitat for fishes off the northeast coast of the United States. Fishery Bulletin. 106(1):93-107.

Wright D, Pendleton M, Boulware J, Walbridge S, Gerlt B, Eslinger D, Sampson D, Huntley E. 2012. ArcGIS Benthic Terrain Modeler (BTM), v. 3.0, Environmental Systems Research Institute, NOAA Coastal Services Center, Massachusetts Office of Coastal Zone Management. Available online at http://esriurl.com/5754.

Appendix A: Shoal Classification Scheme Dictionary

In the following text, superscript next to the unit name indicates the primary source of the definition.
[10] Indicates units or definitions drawn from CMECS text (FGDC 2012).
[24] Indicates definitions drawn from the Rutecki et al. (2015) report. In some cases, the definition is a hybrid of both.

A.1 Shoal Classification Scheme Component Definitions

Biogeographic Setting (EC)

EC units are included to add contextual information to the sediment resources data layer such as prevailing oceanographic conditions. The CMECS *Biogeographic Setting* is a fully hierarchical component. For the purposes of this project, we intend to apply *Ecoregion* units and aggregate upward in the hierarchy if necessary.

Ecoregions:[10] Areas of relatively homogeneous species composition, clearly distinct from adjacent systems. The species composition is likely to be determined by the predominance of a small number of ecosystems and/or a distinct suite of oceanographic or topographic features. The dominant biogeographic forcing agents defining the ecoregions vary from location to location but may include isolation, upwelling, nutrient inputs, freshwater influx, temperature regimes, ice regimes, exposure, sediments, currents, and bathymetric or coastal complexity."

CMECS ecoregions are drawn from the Marine Ecosystems of the World (Spalding et al. 2007) Units relevant to this report consist of the following:

- Scotian
- Gulf of Maine / Bay of Fundy
- Virginian
- Carolinian
- Northern Gulf of Mexico, and
- Floridian

Geoform (GC)

The geomorphology of the seafloor is one of the two primary characteristics of interest in this project. The *Geoform Component* is a semi-hierarchical framework. This project will focus on the physiographic setting, *Geoform* and *Goform Types*, which are hierarchical. It should be noted that like many geomorphic classifications, the definitions are somewhat subjective and there is conceptual overlap between units. Some banks can considered bars, some ridges can be considered shoals, and so on. Nevertheless, these terms are helpful and provide a mental picture of the feature.

Physiographic Setting:[10]

With the geographic scope of this project being the Federal waters of the Atlantic and Gulf of Mexico Exclusive Economic Zone, the only relevant physiographic setting needed was Continental Shelf. As the geography of the tool expands, it is likely that additional CMECS physiographic units may be come relevant and need to be included.

> **Continental/Island Shelf:**[10] That part of the continental margin that is between the shoreline and the continental slope (or a depth or 200 m when there is no noticeable continental slope); it is

characterized by its very gentle slope of 0.1°. Island shelves are analogous to the continental shelves, but surround islands.

For the purposes of this project, where only coarse resolution data may be available, this system proposes adding a provisional *Complex* level to the CMECS Geoform. The proposed units are as follows:

Geoform Complex:**[10]** This is a new provisional CMECS level**.** Geoform complexes consist of many small geoforms within an area or a repeatable assemblage of associated geoforms that function as a system. Examples include salt marshes that contain tidal creeks, marsh platforms, banks and pannes. The *Complex* level should be used when data resolutions are not high enough to distinguish the boundaries of individual geoforms or where the minimum mapping unit consists of multiple geoform units.

> **Shoal Complex:** [24] Two or more shoals (and includes adjacent morphologies, such as troughs separating shoals) that are interconnected by past and or present sedimentary and hydrodynamic processes. An area consisting of several shoals too small to be distinguished individually due to data resolution or mapping constraints.

Geoforms[10] are physical, coastal and seafloor structures that are generally no larger than hundreds of square kilometers in size. This size determination may be an areal extent or a linear distance. Larger geoforms (Level 1) are generally larger than 1 km^2, and correspond to Megahabitats in the Greene et al. (2007) classification system. These features can be defined using geologic or geomorphic maps and bathymetric images of the seafloor at map scales of 1:250,000 or less. Smaller geoforms (Level 2) are generally less than 1 km^2 in size (or less than 1 km in distance); and correspond to Meso- and Macro-habitats in the Greene et al. (2007) system. Level 2 geoforms (such as individual coral reefs, tide pools, and sand wave fields) can be identified through *in situ* observational methods (such as underwater videography) or through low-altitude, high-resolution optical or acoustic remote sensing.

> **Shoal:[10,24]** A natural, underwater ridge, bank, or bar consisting of, or covered by, sand or other unconsolidated material, resulting in shallower water depths ($\geq$ 1 m) than surrounding areas. Morphologically and spatially dynamic, they are primarily shaped by waves and currents and can be driven across the seafloor during tropical storms and hurricanes as well as less intense (but more frequent northern meteorological fronts and other lower intensity events. In some cases, shoals may be exposed during low tides.
>
>> **Moraine Shoal:[10]** The submerged portion of a glacial moraine that reaches close to the surface. These often occur where sea-level rise has drowned former terrestrial glacial features.
>>
>> **Cape-Associated Shoals**:**[24]** Active sedimentary systems that extend from cuspate foreland promontories formed by two barrier islands (Rutecki et al. 2014 figures 2-3 and 2-5) or mainland beach ridges joined at approximately right angles (McNinch and Luettich Jr 2000). Cape-associated shoals form due to the convergence of two longshore drift cells, and as a result of self-organization of the coast in response to a high-angle-wave instability in shoreline shape. Cape-associated shoals can also be influenced by the preexisting geological framework (Rutecki et al. 2014 figure 2-4; Thieler and Ashton 2011)
>>
>> **Bedform Shoals**:**[10,24]** A continuum of morpho-sedimentary bedforms exists along the inner- and mid-continental shelf of siliciclastic passive continental margins. The continuum ranges from sorted bedforms occupying the sediment-starved end of the continuum and linear shoals and shore-attached ridges on the sediment abundant end of the continuum.

Isolated Shelf Shoals:[24] Shoals formed by relict coastal sedimentary processes exposed by ravinement. These are discrete features associated with a single landform or shoreline position.

Geoforms Subtypes are further refined types of geoforms and are fully nested within the Geoform level. Geoform Subtype is a new proposed level for CMECS based on the source data and needs of this project. The two units below are currently the only Geoform Subtypes proposed.

Linear Shelf Sand Ridges:[24] Along the mid-Atlantic coast, linear shore-normal shelf sand shoal complexes are most prominent along the Delaware-Maryland-Virginia inner shelf, where they are the dominant features (Hayes and Nairn 2004; Swift and Field 1981, Figures 2-8 and 2-9). According to Swift and Field (1981), there are three basic types of linear shore-normal shelf sand shoal (called ridge and swale by the authors) morphologies found within the Delaware-Maryland system; they include ***shore-attached ridges*** (0- to 3-m isobaths), ***nearshore ridges*** (6- to 18-m isobaths and within 10 km off shore), and ***offshore ridges*** (greater than 10 km offshore). Each ridge is roughly 3–4 km long and 0.5–1 km wide with ridges spaced 1–4 km apart.

Rippled Scour Depressions:[24] Are bathymetrically subtle, large-scale bed features that are characterized by alternating bands of coarse- and fine-grained sediment with wavelengths of hundreds of meters (Van Oyen et al. 2011), and negative relief of ~ 1 m that trend obliquely to the coast (Guitierrez et al. 2005, Figure 2-6). Where there is a dominant direction of suspended sediment transport, these features tend to be asymmetrical, with coarser flanks facing updrift, into the direction of dominant sediment transport. Where there is no dominant current direction, they tend to be symmetric (e.g., Goff et al. 2005; Diesing et al. 2006). The coarse material is in the troughs (or swales), and the ridges are finer grained. Self-organizing features due to the interaction of frictional sediment transport, bottom composition, and turbulence, with bottom roughness over the troughs causing turbulence that inhibits the settling of fines within the troughs.

Sediment Wave Field:[10] An area of wave-like bedforms in sand or other unconsolidated material, which are formed by the action of tides, currents, or waves. These bedforms range from centimeters to meters in size and may be superimposed on larger features. Sand waves lack the deep scour associated with dunes or megaripples (Bates and Jackson 1984). For this project, these features can be distinguished from other shoals due to their lack of physical relief relative to the surrounding sea floor. They are distinguished from Sediment Sheets by the presence of bedforms (ripples) indicating higher energy and potentially coarser substrates.

Sediment Sheet:[10] A thin, widespread, sedimentary deposit formed by a transgressive sea advancing for a considerable distance over a stable shelf area; may also be called a blanket deposit (Bates and Jackson 1984). For this project, the term will be used to describe unconsolidated substrates lacking bedforms or rippling and without physical relief relative to the surrounding seafloor.

Dredge Deposit:[10] An accumulation on the seafloor (or land surface) where spoil materials from a dredging operation are placed. They often exhibit some topographical expression and can support biological communities that are different than the surrounding area. These deposits are often unconsolidated in character, but they can also be relatively stable.

Dredge Deposit Shoal:[10] A subaqueous area that is substantially shallower than the surrounding area, which resulted from the deposition of materials from dredging and dumping.

Substrate Component (SC)

Classification units for describing the surficial substrate will draw directly from the CMECS SC. This is a fully hierarchical framework organized by substrate origin (geologic, biogenic, and anthropogenic). Most units to be applied in this project are from the Unconsolidated Sediments Class, which has sub-units based on Wentworth grain size fractions. The Biogenic Shell Substrate class is included because source literature indicates that the presence and amount of shell hash is important to fish habitat value.

It is unlikely that actual grain size information necessary to classify substrate to the group or subgroup level will be available throughout the project geography; therefore, the definitions below are at the CMECS subclass level. Definitions for *Substrate Group* and *Substrate Subgroup* levels can be found at https://iocm.noaa.gov/cmecs.

Substrate Subclasses:[10] are determined by the composition and particle size of the dominant substrate origin in the surface sediments. Class and subclass definitions represent a merging of approaches from Wentworth (1922), Folk (1954), and the FGDC-STD-004.

> **Coarse Unconsolidated Substrate:**[10] Geologic Substrate surface layer contains > 5% Gravel (particles 2 mm to < 4,096 mm). These sediments are classified using the upper three rows of the Folk (1954) Gravel-Sand-Mud diagram.
>
> **Fine Unconsolidated Substrate:**[10] Geologic Substrate surface layer contains less than 5% gravel (particles 2 mm to < 4,096 mm in diameter). These sediments are classified using the bottom two rows of the Folk (1954) Gravel-Sand-Mud diagram and the entire Folk (1954) Sand-Silt-Clay diagram.
>
> **Shell Hash:**[10] Surface substrate layers are dominated by loose shell accumulations with a median particle size of 2 mm to < 64 mm (Granules and Pebbles). Shells may be broken or whole. The presence of Shell Hash is noted in this subclass (and in the following groups).
>
> **Shell Sand:**[10] Biogenic Substrate layers that are dominated by Sand that is primarily composed of shell particles with a median particle size of 0.0625 mm to < 2 mm (Sand). Shells or remains are generally broken and difficult to identify. For this reason, only substrate-forming taxa that produce distinctive Sand types are listed as substrate groups. When the composition and origin of Sand is unclear, it is assumed to be mineral Sand and is classified as a Geologic Origin substrate.

Biotic Component (BC)

The CMECS Biotic Component focuses on living organisms of the water column and seabed at a variety of scales. The BC is organized into a branched hierarchy of five nested levels: Biotic Setting, Biotic Class, Biotic Subclass, Biotic Group, and Biotic Community. The biotic setting indicates whether the biota are attached or closely associated with the benthos or are suspended or floating in the water column. Biotic classes and biotic subclasses describe major biological characteristics at a fairly coarse level. Unless otherwise noted, biotic classification units are defined by the dominance of life forms, taxa, or other classifiers in an observation. For collected observations (such as grab samples or cores), dominance is measured in terms of biomass or numbers of individuals, as specified by the user. In the case of images and visual estimates, dominance is assigned to the taxa with the greatest spatial percent cover in the observational footprint (image footprint or field of view).

Based on the source data available for the project, it is expected that only the Biotic Setting and Biotic Class units would be useful. Of these only a subset would be expected to occur in the project study area. These are defined below.

Planktonic Biota[10]: This setting includes biota that drift, float, or remain suspended in the water column in aggregations that are big enough to be (a) detected by the human eye (or with mild magnification) or (b) sampled with a fine-plankton net. Planktonic biota are not regularly associated with the seafloor.

Zooplankton:[10] Zooplankton are heterotrophic biota of the water column; zooplankton drift with the currents, but may (or may not) be able to move through the water under their own power. CMECS classifies zooplankton that may range in size from gigantic salp chains (strings of gelatinous filter feeding tunicates that attain a length of 30 m or more), to radiolarians (minute, shelled amoebas). CMECS was not designed to be used for the smallest planktonic forms (nanoplankton or picoplankton). CMECS Class Zooplankton includes both Holoplankton (that live out their entire life histories in the plankton) and Meroplankton (that are transient in the plankton).

Floating/Suspended Plants and Macroalgae:[10] This class includes areas dominated by vascular plants, detached plant parts, or macroalgae that are floating on the surface or are suspended in the water column—that is, plants and macroalgae that are not rooted or attached to the bottom.

Phytoplankton:[10] This class includes areas of floating or suspended microscopic algae that are capable of photosynthesis. Although some species are motile, they are generally passively transported by water movements. Under certain conditions, they can form aggregations, large blooms, or colonies.

Floating/Suspended Microbes:[10] Aggregations of microbes that are floating or suspended in the water column and not attached to the bottom or to any benthic substrate.

Benthic Biota[10]: This biotic setting describes areas where biota lives on, in, or in close association with the seafloor or other substrates (e.g., pilings, buoys), extending down to include the layers of sediment that contain multi-cellular life.

Reef Biota:[10] Areas dominated by reef-building fauna, including living corals, mollusks, polychaetes, or glass sponges. In order to be classified as Reef Biota, colonizing organisms must be judged to be sufficiently abundant to construct identifiable biogenic substrates. When not present in densities sufficient to construct reef substrate, the biota is classified in the Aquatic Vegetation Bed or Faunal Bed classes.

The Reef Biota Class refers to only the living component of reef structures. If referring to the reef structure, users should use the reef units in the Geoform Component. If referring to the composition of the reef substrate independent of the living cover, users should employ the Coral Substrate, Shell Substrate, or Worm Substrate Classes in the SC.

Faunal Bed:[10] In this class the seabed is dominated or characterized by a cover of animals that are closely associated with the bottom, including attached, clinging, sessile, infaunal, burrowing, laying, interstitial, and slow moving animals, but not animals that have created substrate (Reef Biota). Unlike Reef Biota, Faunal Bed biota cannot (or are not sufficiently abundant to) construct identifiable substrate. "Slow moving" animals included in the Faunal Bed class are defined as being incapable of moving outside the boundaries of the classification unit within one day. Faunal Bed organisms are aquatic, but they may be able to withstand periods of exposure to air.
Faunal Bed food webs may receive basic trophic inputs from benthic photosynthesis or chemosynthesis, plankton, allochthonous detritus and debris, or other sources. In nature, Faunal Bed habitats are often composed of complex mixes and associations of animals of different phyla,

sizes, feeding strategies, and habits, and these areas can be difficult to classify. Faunal Bed classifications are determined in CMECS by greatest percent cover of fauna or faunal structures, or (particularly for infauna) by estimates of greatest biomass.

Microbial Communities:[10] These are areas dominated by colonies of microscopic or single-celled organisms that form a hard structure, visible film, layer, or mat on or near the surface of the substrate. Colonies may be composed of benthic microalgae (e.g., diatoms), photosynthetic bacteria (e.g., cyanobacteria), archaea, saprotrophic bacteria (e.g., decomposers or decay organisms), chemoautotrophic bacteria, or other microbial groups. These features may exist on or near the surface of the sediment either subtidally or subaerially, or they may exist as extensive areas of decay associated with dead organisms that have fallen to the seafloor.

The additional remaining CMECS Classes of **Aquatic Vegetation Bed**, **Emergent Wetland**, and **Scrub-Shrub Wetland** are not expected to occur in the project study area and are not included in this data dictionary.

Modifiers (M)

Modifiers further describe classification units and can be applied as needed and where source data supports their use. In some cases, modifiers may themselves be mapping units (e.g., rugosity grids). Modifers for use in this project are grouped as follows:

Anthropogenic Modifiers

Dredged:[10] Landscape that is mechanically altered by the removal of sediments or other materials (e.g., shell) in order to deepen or widen channels (e.g., for navigation or alteration to hydrology).

Filled Deposition Site:[10] Areas where materials (such as sand or shell) have been placed on (or in) an area of coast or a water body.

Physical Modifiers

Energy Direction:[10] Energy can be classified according to its principal direction of travel or influence. In the case of tidal energy, this is generally an oscillation between onshore and offshore motions. In the case of currents and waves, the energy is usually directional.

Baroclinic	Motion along lines of equal pressure within the water column
Circular	Motion in a closed, circular form
Downward	Descending and perpendicular to the sea surface or bottom
Horizontal	Parallel to the sea surface or bottom
Mixed	Combination of more than one of above directions
Seaward	On land, water currents following a topographic gradient toward the sea
Upward	Ascending and perpendicular to the sea surface or bottom

Energy Intensity:[10] Energy Intensity is classified into four categories as shown. Additional terms may be applied in this system as necessary to better reflect conditions at the sediment/water interface.

Very Low Current Energy	Area experiences little current motion under most conditions
Low Current Energy	Area typically experiences very weak currents (0–1 knots)
Moderate Current Energy	Area regularly experiences moderate tidal currents (> 1–3 knots)
High Current Energy	Area regularly experiences strong currents (> 3 knots)

Energy Type:[10] The Energy Type Modifier is adapted from Dethier (1990) and Zacharias et al. (1998) with type categories as follows:

Current	Coherent directional motion of the water
Internal Wave	Vertical and transverse oscillating water motion, below the surface, due to seismic energy or a pressure differential
Surface Wave	Vertical and transverse oscillating surface water motion due to wind or seismic energy
Tide	Periodic, horizontally oscillating water motion
Wind	Coherent directional motion of the atmosphere

Seafloor Rugosity:[10] Seafloor rugosity, a measure of surface "roughness," is applicable at several scales using different measures (e.g., bathymetric x-y-z data, measured transect data, video data). Rugosity is derived as the ratio of surface area to planar (flat) area for a grid cell, or as the ratio of surface area to linear area along transects, and is calculated as follows:

$$fr = Ar / Ag$$

where Ar is the real (true, actual) surface area and Ag is the geometric surface area (IUPAC 1997).

Values for Seafloor Rugosity are taken from Greene et al. 2007. The five rugosity types and their associated numeric values are shown below

Very Low	1.0 to < 1.25
Low	1.25 to < 1.50
Moderate	1.50 to < 1.75
High	1.75 to < 2.00
Very High	≥ 2.00

Rugosity Value: Recognizing that small differences in rugosity may be important to the habitat value of certain biota, this field will be populated by the actual rugosity value and not assigned to one of the more general CMECS categories.

Slope:[10] The Slope modifier refers to the angle of the substrate at a scale appropriate for the feature being described; Greene et al.'s (2007) geological classification is followed here to characterize slope.

Substrate Descriptors:[10] Although the CMECS SC describes substrate size and composition, following Wentworth (1922) and Folk (1954) to describe particle sizes and mixes, it generally does not consider geologic composition or several other important attributes. The following substrate descriptors provide consistent terminology to meet the needs of this project.

Carbonate	Geologic Origin particles or substrates composed mainly of carbonate minerals (e.g., limestone, dolostone).
Compacted	Unconsolidated sediments with very little water content and a hard, packed form that resists penetration and resuspension. This is one of several terms that are used in CMECS to describe the fluid consistency of substrates.
Mobile	Bedded sediments which regularly re-suspend and/or move with local hydrodynamics due to the density, grain size, shape, and/or high water content of the sediment, or due to the higher hydrodynamic energy experienced in the local area. This term and the corresponding term Non-Mobile are used in CMECS to describe or predict behavior of substrates.
Non-mobile	Bedded sediments that do not regularly re-suspend and/or move with local hydrodynamics due to the density, grain size, shape, and/or compaction (low water content) of the sediment particles, or due to the lower hydrodynamic energy experienced in the local area.
Patchy	Different elements within a sample, observational unit, or reporting unit are grouped into clusters or patches at the scale of the sample or unit. "Patchy" implies that clusters of elements or particles are arranged in a haphazard manner, as clusters of pebbles scattered on sand. This is one of several terms used in CMECS to describe unit variability.
Siliciclastic	Geologic Substrate Origin particles or substrates composed primarily of silicate minerals, e.g., quartz, sandstone, siltstone.
Sulfidic	Substrate in which bacterial sulfate reduction is an important biogeochemical process; this generally occurs in anaerobic environments, is often identifiable by a very low reflectance black or blue color, and is a characteristic "rotten egg" odor when sediments are examined in air.
Volcaniclastic	Geologic Origin particles or substrates composed primarily of volcanic rock, crystals, glassy pumice, ash, or other volcanic products.
Volcanic Ash	A substrate or substrate layer composed primarily of volcanic dust and volcanic ash, often with various aeolian or marine-generated particles mixed in. In areas of the deep sea, where terrigenous input and bioturbation are limited, Volcanic Ash may be present in distinct layers at depth in the substrate matrix (see the "Layers" modifier).

Well-mixed	Different elements within a sample, observational unit, or reporting unit are well-mixed or poorly sorted at the scale of the sample or unit. Well-mixed implies that elements or particles are completely and relatively evenly intermingled, e.g., Granule/Sand/Mud particles in an area with high bioturbation. This is one of several terms used in CMECS to describe unit variability. Note that CMECS does not use the equivalent geological term "Poorly Sorted," because the descriptor may be used to describe distributions of non-geological features (such as biological communities or Geoform Component structures).
Well-sorted	Different elements within a sample, observational unit, or reporting unit are separated into different areas at the scale of the sample or unit. Well-sorted implies that elements or particles are (or have been) separated and arranged in a non-haphazard manner, as an area of Coarse Sand adjacent to an area of Clay. This is one of several terms used in CMECS to describe unit variability.
Heterogenous	A diverse complex substrate pattern that contains multiple pattern types or may be applied in situations where there is evidence of several patterns, but resolution of the data does not allow discrimination of the individual types.

Surface Pattern:[10] These roughness patterns may have physical origins (e.g., caused by wave or current action) or biological origins (due to activities of life forms, e.g., mounds or tunnels).

Biological	Roughness appears due to bioturbation, fecal mounds, tunneling, feeding or locomotory activities of megafauna, or other faunal activities. Further characterization of biological features is described in the Biotic Component.
Irregular	Sediment surface has a perceptible roughness or texture that is non-regular in either frequency, direction, or amplitude.
Physical	Roughness appears due to water motion, but the nature of the roughness is other than Rippled.
Rippled	Closely spaced, regular, repeating, vertical variations in the height of a sandy or muddy bottom, with a very short wavelength on the order of centimeters. A rippled substrate is generally caused by the physical processes of water motion.
Scarred	Roughness appears due to localized sediment disturbance resulting either from natural causes (e.g., slumps) or anthropogenic causes (e.g., anchor scars, propeller scars, trawl scars, or other fishing gear scars), but not as an artifact of camera or sampling gear deployment.
Smooth	There is no perceptible roughness or texture to sediment surface at scales of less than 1 m.
Heterogenous	The surface has a complex mix of patterns or the pattern appears mixed but cannot be further described due to insufficient resolution of the data.

Physiochemical Modifiers

Oxygen Regime:[10] For the purposes of this project actual dissolved oxygen minimum values will be reported rather than the range categories in CMECS. These values will be reported in mg/liter.

Spatial Modifiers

Benthic Depth Zone:[10] These are generally based on the zones in which surf or ocean swell influences bottom communities, lower limits of vegetation (such as kelp), overall photic availability, and temperature. The zones within this category are drawn or adapted from Greene et al. (2007) and Connor (1997). The following definitions are intended as guidance for adaptation of depth ranges to regional environmental conditions:

Shallow Infralittoral	0 to < 5 m deep
Deep Infralittoral	5 to < 30 m deep
Circalittoral	30 to < 200 m deep

Temporal Modifiers

Temporal Persistence:[10] The Temporal Persistence Modifier describes the permanency or variability of a hydromorphic, geomorphic, or biological feature. Though qualitative and relative, it is useful is distinguishing between features that are similar in morphology—but are temporally diverse in terms of stability. For this project this will refer to the physical integrity of a feature (shoal, ridge, etc.) and over what time period it maintains its shape. The following CMECS temporal persistence units are included in this project:

Months

Years

Inter-Annual

Decades

Centuries

Additional Modifiers (M)

A series of additional modifiers or descriptive units have been considered potentially valuable to assessing the character of sand resources/shoals. These are intended to characterize the spatial relationship of individual features to the surrounding landscape and understand their longevity and integrity, which may be important to their long-term function as fish habitat. It is understood that further research, spatial analysis, and time-series information will be needed to apply these modifiers with confidence. As data becomes available to conduct these types of analysis, it is expected that they will become part of the shoals descriptive database.

Benthic Depth Zone:[10] These are generally based on the zones in which surf or ocean swell influences bottom communities, lower limits of vegetation (such as kelp), overall photic availability, and temperature. The zones within this category are drawn or adapted from Greene et al. (2007) and Connor (1997). The following definitions are intended as guidance for adaptation of depth ranges to regional environmental conditions:

Shallow Infralittoral	0 to < 5 m deep
Deep Infralittoral	5 to < 30 m deep
Circalittoral	30 to < 200 m deep

Feature Orientation: Feature orientation is a reflection of the cardinal direction of the longest axis of a shoal, ridge, or other bathymetric feature. This will be expressed as a numeric value in degrees based on a geographic compass rose.

Positional Stability: This expresses the likelihood of an ephemeral feature changing geographic location while still generally maintaining its structure and size. Positional stability is most relevant in capturing the movement across the seascape of sand waves, dunes, etc. Units for this modifier are still in development and will be informed by time-series data.

Accretion Status: This is a measure of whether a feature (shoal, bank, ridge, dune, or bar) is growing in volume and extent due to sediment accretion or shrinking due to erosion. In cases where neither process is underway or where both processes are cancelling each other out, then the status would be neutral. Accretion status can only be assessed in the context of a timeframe. A window of at least 3 years is needed for BOEM borrow areas.

Shelf Position: This is a relative description of the spatial location of a feature on the continental shelf. Units for this modifier are still in development and will be determined by the source data.

Bathymetric Position Index (BPI): Output slope values (raster grids) are derived for each cell as the maximum rate of change from the cell to its neighbor. BPI is a second-order derivative of bathymetry modified from topographic position index as defined in Weiss (2001) and Iampietro and Kvitek (2002).

Standard Deviation of Depth: This metric will be applied to characterize the frequency (distance between ripple crests) and amplitude (height of crest above trough) of ripples and systematically repeating bedforms.

Disturbance Regime: This is measure of how often the surface of the substrate is disturbed or re-worked by storm events or strong ocean currents. Disturbance regimes of months to years are appropriate for sediment deposits in Federal waters less than 50 m deep.

A.2 References Used in Scheme Definition

Auster P.J., J. Moore, K.B. Heinonen, L. Watling. 2005. A Habitat Classification Scheme for Seamount Landscapes: Assessing the Functional Role of Deep-Water Corals as Fish Habitat, In: Freiwald A., Roberts J.M. (eds) Cold-Water Corals and Ecosystems. Erlangen Earth Conference Series. Berlin, Heidelberg: Springer,

Auster PJ, Heinonen KB, Witharana C, McKee M. 2009. A habitat classification scheme for the Long Island Sound region. Long Island Sound Study Technical Report. EPA Long Island Sound Office, Stamford, Connecticut. 06904. 83 pp.

Bates RL, Jackson JA, eds. 1984. Dictionary of geological terms. 3rd ed. Garden City (NY): Anchor Press.

Connor DW. 1997. Marine biotope classification for Britain and Ireland. Peterborough (UK): Joint Nature Conservation Review.

Cullis S, Colombera L, Patacci M, McCaffery WE. 2018. Hierarchical classifications of sedimentary architecture of deep marine depositional systems. Earth-Science Reviews. 179: 38-71.

Davies J, Guillaumont B, Tempera F, Vertino A, Beuck L, Ólafsdóttir S, Smith C, Fosså J, Van den Beld I, Savini A. 2017. A new classification scheme of European cold-water coral habitats: implications for ecosystem-based management of the deep sea. Deep Sea Research Part II: Topical Studies in Oceanography. 145:102-109.

Diesing M, Kubicki A, Winter C, Schwarzer K. 2006. Decadal scale stability of sorted bedforms, German Bight, southeastern North Sea. Continental Shelf Research. 26: 902-916.

Dethier M. 1990. A marine and estuarine habitat classification system for Washington State. Washington State Department of Natural Resources.

Dove D, Bradwell T, Carter G, Cotterill C, Gafeira J, Green S, Krabbendam M, Mellet C, Stevenson A, Stewart H, Westhead K, Scott G, Guinan J, Judge M, Monteys X, Elvenes S, Baeten N, Dolan M, Thorsnes T, Bjarnadottir L, Ottesen D. 2016. Seabed Geomorphology: A Two-Part Classification System. British Geological Society, Marine Geoscience Programme, Open Report OR/16/001.

FGDC (Federal Geographic Data Committee). 2012. Coastal and Marine Ecological Classification Standard. Reston (VA). Federal Geographic Data Committee, Marine and Coastal Spatial Data Subcommittee. FGDC-STD-018-2012.

Folk RL. 1954. The distinction between grain size and mineral composition in sedimentary-rock nomenclature. The Journal of Geology. 62: 344-359.

Goff JA, Mayer LA, Traykovski P, Buynevich I, Wilkens R, Raymons R, Glang G, Evans RL, Olson H, Jenkins C. 2005. Detailed investigation of sorted bedforms, or 'rippled scor depression,' within Martha's Vineyard coastal observatory, Massachusetts. Continental Shelf Research. 25: 461-484.

Greene HG, Yoklavich MM, Starr RM, O'Connell VM, Wakefield WW, Sullivan DE, McRea JE, Cailliet GM. 1999. A classification scheme for deep seafloor habitats. Oceanologica Acta. 22(6):663-678.

Greene HG, Bizzarro JJ, O'Connell VM, Brylinsky CK. 2007. Construction of digital potential marine benthic habitat maps using a coded classification scheme and its applications. In: Todd BJ, Greene HG, editors. Mapping the seafloor for habitat characterization. Geological Association of Canada. Special Paper 47. 141–155 pp.

Guitierrez BT, Voulgaris G, Thieler ER. 2005. Exploring the persistence of sorted bedforms on the inner-shelf of Wrightsville Beach, North Carolina. Continental Shelf Research. 25: 65-90.

Harris P and Baker E. 2012. GeoHAB Atlas of seafloor geomorphic features and benthic habitats. ISBN 978-0-12-385140-6

Hayes MO, Nairn RB. 2004. Natural maintenance of sand ridges and linear shoals on the U.S. Gulf and Atlantic continental shelves and the potential impacts of dredging. Journal of Coastal Research. 20(1):138–148.

Hill, N, Althaus F, Rees T, Jordan A, Colquhoun J, Schonberg C, Case M, Scott F, Edgar G, Legorreta RF, Fromont J, Przeslawski R, Hayes K, Marzinelli Z, FriedmanA, Toohey L, Hibberd T, Hovey R, Kendrick G, Wyatt M. 2014. CATAMI Classification scheme for scoring marine biota and substrata in underwater imagery-Version 1.4. (catami.org)

Hume TM, Herdendorf CE. 1988. A geomorphic classification of estuaries and its application to coastal resource management—a New Zealand example. Ocean and Shoreline Management. 11(3):249-274.

Iampietro P, Kvitek R. 2002. Quantitative seafloor habitat classification using GIS terrain analysis: effects of data density, resolution, and scale. In: Proceedings of the 22nd Annual ESRI User Conference; San Diego, CA; July 8-12.

INFOMAR. 2017. INFOMAR Seabed Survey Seabed Habitat Classification System. (https://data.world/geological-surv/8bf2cf66-8eb8-4a06-bb83-8304ee96c313)

IUPAC. 1997. Compendium of chemical terminology, 2nd ed. (the "Gold Book"). Compiled by A. D. McNaught and A. Wilkinson. Oxford (UK): Blackwell Scientific Publications. XML on-line corrected version: http://goldbook.iupac.org (2006-) created by M. Nic, J. Jirat, B. Kosata; updates compiled by A. Jenkins.

McNinch JE, Luettich Jr RA. 2000. Physical processes around a cuspate foreland: implications to the evolution and long-term maintenance of a cape-associated shoal. Continental Shelf Research. 20(17): 2367-2389.

Rutecki D, Dellapenna T, Nestler E, Scharf F, Rooker J, Glass C, Pembroke A. 2014. Understanding the habitat value and function of shoals and shoal complexes to fish and fisheries on the Atlantic and Gulf of Mexico Outer Continental Shelf literature synthesis and gap analysis. Herndon (VA): US Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM 2015-012. 187 pp.

Spalding MD, Fox HE, Allen GR, Davidson N, Ferdana ZA, Finlayson M, Halpern BS, et al. 2007. Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. BioScience. 57(7):573–583.

Swift DJP, Field ME. 1981. Evolution of a classic sand ridge field: Maryland secor, North American inner shelf. Sedimentology. 28:461-482.

Thieler ER, Ashton AD. 2011. ‘Cape capture’: geologic data and modeling results suggest the Holocene loss of a Carolina Cape. Geology. 39:339-342

Van Oyen T, de Swart H, Blondeaux P. 2011. Formation of rhythmic sorted bed forms on the continental shelf: an idealistic model. Journal of Fluid Mechanics. 684:475-508.

Weiss AD. 2001. Topographic positions and landforms analysis [conference poster]. ESRI International User Conference; San Diego, CA; Jul 9–13.

Wentworth CK. 1922. A scale of grade and class terms for clastic sediments. The Journal of Geology. 30:377–392.

Zacharias MA, Howes DE, Harper JR, Wainwright P. 1998. The British Columbia marine ecosystem classification: rationale, development, and verification. Coastal Management. 26:105–124.

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