ANALYSIS OF POTENTIAL BIOLOGICAL AND PHYSICAL IMPACTS OF DREDGING ON OFFSHORE RIDGE AND SHOAL FEATURES

FINAL REPORT

Prepared for:
U.S. Department of the Interior
Minerals Management Service
Leasing Division
Marine Minerals and Alternative Energy Branch

OCS Study
MMS 2010-010

Final Report

ANALYSIS OF POTENTIAL BIOLOGICAL AND PHYSICAL IMPACTS OF DREDGING ON OFFSHORE RIDGE AND SHOAL FEATURES

Contract Number 1435-01-03 CT-72020

March 2010

Prepared for:

U.S. Department of the Interior
Minerals Management Service
Leasing Division
Marine Minerals and Alternative Energy Branch

Prepared by:

CSA International, Inc.
8502 SW Kansas Avenue
Stuart, Florida 34997
Telephone: 772-219-3000

In cooperation with:

Applied Coastal Research and Engineering, Inc.
Barry A. Vittor & Associates, Inc.
C.F. Bean, L.L.C.
Florida Institute of Technology

DISCLAIMER

SUGGESTED CITATION

CSA International, Inc., Applied Coastal Research and Enginnering, Inc., Barry A. Vittor & Associates, Inc., C.F. Bean, L.L.C., and Florida Institute of Technology. 2009. Analysis of Potential Biological and Physical Impacts of Dredging on Offshore Ridge and Shoal Features. Prepared by CSA International, Inc. in cooperation with Applied Coastal Research and Engineering, Inc., Barry A. Vittor & Associates, Inc., C.F. Bean, L.L.C., and the Florida Institute of Technology for the U.S. Department of the Interior, Minerals Management Service, Leasing Division, Marine Minerals Branch, Herndon, VA. OCS Study MMS 2010-010. 160 pp. + apps.

ACKNOWLEDGMENTS

This project was conceived and funded by the U.S. Department of the Interior, Minerals Management Service (MMS). Ms. Colleen Finnegan provided assistance and direction during the project as the MMS Contracting Officer's Technical Representative. Ms. Debra Bridge served as the MMS Contracting Officer. We gratefully acknowledge their guidance in the conduct of this project. We also thank Ms. Kristen Metzger of CSA International, Inc. for assistance in literature and data collection. Ms. Kim Dunleavy and Ms. Melody Powell provided editorial assistance, and Ms. Karen Stokesbury supervised CSA International, Inc. support staff during production of the report.

EXECUTIVE SUMMARY

The Minerals Management Service (MMS) is responsible for managing exploration and development of mineral resources on submerged Federal Outer Continental Shelf (OCS) lands in an environmentally sound and safe manner, including sand deposits. The OCS contains large sand deposits that are expected to serve as long-term sources of borrow material for beach nourishment and coastal restoration projects. Potential for exploitation of these resources has grown rapidly in the last several years with identification of suitable sand resource areas in some OCS regions. Demand for high quality sand suitable for beach nourishment, coastal protection, and other public and private projects is anticipated to increase during coming years.

Coastal jurisdictions recently have become more interested in sand resources seaward of State waters for several reasons. Onshore sources of suitable sand that were once abundant are now becoming scarce due to deposit depletion, competing uses, and urban development. For large nourishment projects, transporting sand from nearshore areas often is far more economical than trucking sand from upland sources. Like onshore sources, nearshore sand resources often are limited, diminishing in supply, and/or polluted, necessitating the need for alternative deposits that exist farther offshore. Using offshore deposits provides the important benefit of adding sand to the beach/nearshore system, rather than simply moving sand from one part of the system (nearshore) to another (beach). Furthermore, sand resources in Federal waters may be environmentally preferable due to concerns that extraction of large quantities of sand and gravel from nearshore sites can change the bathymetry of an area and result in modifications to existing physical oceanographic conditions.

Offshore sand resources have become an important component of the U.S. Army Corps of Engineers (USACE) projects that focused on beach nourishment for coastal erosion control. Shelf sand ridges are common along the Atlantic and Gulf coasts of the United States and serve as good potential sources of suitable sand for beach nourishment projects. Considerable variability in geomorphic and sedimentologic characteristics exists as a function of sediment source, and dominant wave and current processes contribute to the suitability of individual sand ridges as a sand source.

The objective of this study was to examine and evaluate the potential biological and physical effects of offshore dredging within the ridge and swale features on the Federal OCS and to suggest engineering options and mitigation measures that can be implemented to avoid potential deleterious impacts, while allowing for the selective removal of needed volumes of sand for nearby beach projects. Research Planning, Inc. et al. (2001) identified several information gaps with respect to physical and biological effects of dredging on sand shoals. The authors framed these gaps as questions, four of which provided much of the impetus for the present study. The questions, in the order given by Research Planning, Inc. et al. (2001), are as follows:

- What is the use and role of sand ridges and shoals as potential essential fish habitat (EFH) by migrating or resident fish?
- Is there a preferred manner to remove sand from a shoal/ridge feature to maximize their use and maintain the integrity of the feature?
- Are there benthic biological differences that run longitudinally along the ridge and shoal features that may affect the proposed sampling design and require further stratification?

- Are there procedures to dredge shoal and ridge features that will minimize ecological impacts and/or speed recovery, such as dredging completely one specific shoal or ridge and leaving adjacent features untouched vs. dredging a small amount of sand from each shoal or ridge feature, or dredging in strips leaving undisturbed areas that act as local sources of recruitment and allow recruitment from older life stages, as supported by the work conducted by Whitlatch et al. (1998)?

Although inter-related, these questions do not follow a strict logical sequence with one another. For this report, connections between questions related to physical effects and their expected biological response are made when possible. The first and third questions pertain to spatial distribution of invertebrate assemblages and habitat use by fishes. The second and fourth questions are concerned with minimizing direct physical impacts to shoals in ways that facilitate biological recovery. A primary goal of this report is to link physical effects of dredging to direct and indirect biological effects and suggest ways to reduce impacts and speed recovery while still effectively mining sand resources. Potential dredging impacts outside of the study area model domain were not evaluated as part of this project (e.g. potential impacts at the shoreline). However, previous MMS studies have reported on these potential impacts (e.g., Byrnes et al., 2004; Maa et al., 2004; Kelley et al., 2004).

TECHNICAL APPROACH

To accomplish the study objective, a technical approach consisting of a series of steps was developed to compile and analyze technical information required to answer the aforementioned study questions. The first step was to collect pertinent published and unpublished results on ridges, shoals, and swales from author libraries, other private and public libraries, and internet websites (**Section 1.1**). After compiling baseline information on offshore shoal fields, a review of dredging procedures for sand mining at these sites was summarized for cutterhead dredges, hopper dredges, and other offshore dredging equipment and techniques as described in **Section 2.0**. Before considering potential impacts of offshore sand mining on physical processes and biological communities at offshore sites, a review of physical impact producing factors associated with sand mining within the study area was completed (**Section 3.0**).

Potential concerns regarding biological community impacts were analyzed by reviewing pertinent studies to ascertain the role of ridges, shoals, and swales as Essential Fish Habitat (EFH) using a cross-shelf analysis framework. The cross-shelf approach was chosen because EFH is broadly defined as "those waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity," which covers the full spectrum of life histories and habitats rather than only ridges, shoals, and swales. Furthermore, a review of pertinent studies to ascertain patterns of benthic biological differences across ridges, shoals, and swales was conducted. The results of these analyses are presented in **Section 4.0**.

After pertinent background information was compiled and analyzed, existing knowledge of borrow site geometries was contemplated relative to environmental and economic considerations. Dredging equipment and techniques were evaluated, and sand mining scenarios were designed taking into account the natural, long-term evolution of the shoal. Potential shoal dredging scenarios specified by the MMS were considered when developing the following sand mining scenarios for simulating shoal changes and potential responses: 1) dredging a hole over a designated area on the shoal; 2) dredging the leading edge of a shoal; 3) dredging the trailing edge of a shoal; and 4) dredging in a striped pattern to facilitate recruitment of benthic invertebrates into dredged areas (**Section 5.1**).

Numerical modeling was completed to provide baseline information regarding potential physical impacts, as well as to evaluate potential physical impact producing factors (i.e., sediment removal, suspension/dispersion [turbidity], deposition [changes in sediment thickness and grain size], and other potential physical disturbances from dredging and positioning equipment) concerning potential biological impacts of dredging offshore ridge and shoal features. Emphasis was placed on estimating the physical impact producing factors associated with the selected dredging scenarios that could be applicable to evaluating near-field and far-field, and short-term and long-term biological impacts (**Section 5.2**).

The results of simulated offshore sand mining scenarios were then analyzed relative to potential impacts on biological communities. Underlying questions regarding potential biological and physical impacts of sand mining at offshore shoals were answered, and dredging scenario alternatives were reported within the context of minimizing ecological impacts and/or enhancing shoal recovery (**Section 6.0**). Finally, recommendations for dredging options and mitigation measures were provided in **Section 7.0**.

DREDGING AT RIDGES AND SHOALS

There are two types of dredges commonly used in the removal of sediment from ridges, shoals, and other types of offshore borrow areas -- hydraulic cutterhead dredges and trailing suction hopper dredges. Two other types of dredges that may used on rare occasions are the dustpan dredge and the Punaise (or “thumbtack”).

Hydraulic cutterhead dredges incorporate the use of a cutterhead near the suction mouth to dislodge the excavated material from the seafloor and assist in the slurrification of the sediment for removal by the suction mouth of the dredge. Dredged material is transported up the suction mouth and propelled away from the dredge via a centrifugal dredge pump. Sediment is transported through a pipeline to the destination, where it is either shaped into the desired fill dimensions or stockpiled for further rehandling.

Hopper dredges are commonly used in offshore conditions where exposure to sea conditions can adversely impact productivity and efficiency of other types of dredges. They often are configured like a ship with a cargo hold designed for dredged material. They are equipped with one to three dragarms, which are pipe structures suspended down the side of the hull to the seafloor. Dredged material is removed from the bottom through the dragarms and placed in the cargo hold of the vessel for transport. The vessel transports the material to a remote location for discharge through the bottom of the hull or for discharge from the hull through a pipeline.

The dustpan dredge is ideal for excavation of granular sediment. Dustpan technology relies on agitation of the bottom sediments through the use of water jets near the suction head to excavate and remove sand from the seabed. This technology works well in sediments that are relatively clean, free from silt, mud, and shell or shell fragments. High velocity water jets are injected into the sediment along the top or bottom of the dustpan head. As the dredge pulls itself forward, the jets collapse, slurrify, and remove the sediments that fall in front of the suction mouth.

The Punaise, or “thumbtack,” is used to mine sand in either the offshore or inland environments, but has the limitation that significant banks of sand are required to make it a productive device. The Punaise consists of a watertight housing containing the dredge pump, motor, and ballast tanks and is connected to the shore station via an umbilical that comprises control connections, power supply, and a slurry discharge line. Once positioned at the appropriate location, the ballast tanks are filled, the Punaise settles to the bottom, and water jet nozzles are then activated, which allows the vertical support to settle into the sand bottom so the dredging process can begin. While in operation, the Punaise rests on the bottom of the seabed and excavates sediment by means of hydraulic erosion and agitation.

Several techniques that can be used in dredging sand ridges and shoals are the following:

- Deep mining (glory hole) has been a method of mining sand in the offshore environment in the past that would yield the maximum productivity and cost efficiency for removal. This technique simply involves placing the suction mouth of the dredge, with or without an agitation device like a cutter, on the seabed and continuing to lower the suction depth until the borrow pit yield diminishes. When the sand quits flowing to the suction mouth, the dredge is advanced or moved to a new location.
- Thin layer removal is often required when there is only a thin layer of suitable material (less than 1.8 to 2.4 m thick) available for a project. There are numerous implications associated with thin layer availability and removal. The thin layer could be overlain and underlain by unsuitable material. Unsuitable material could be defined as a very fine silty mud or a layer of very rocky sediments, neither of which might be considered as suitable for the renourishment project.
- Aggressive, maximum spillage is a method of removal that is common when the sediment transportation capability of the dredge is sufficient to permit a high percentage concentration by volume of sediment in the slurry. A dredge can move through a bank of material with a high percent of spillage, 40% to 60%, and maintain a high production and lower cost.
- Slow, minimum spillage is a method that results in a spillage factor as low as 15% to 20% with a much lower productivity and higher cost implications. This method may be chosen when available borrow material is limited and a more complete evacuation of the borrow area may be necessary to achieve the necessary quantities.

IMPACT PRODUCING FACTORS

Dredging at offshore shoals and ridges creates several physical factors that will produce impacts on biological resources associated with these features. As general categories, these physical factors are

- Sediment removal;
- Turbidity; and
- Sediment deposition.

Removal of sediments from borrow sites can alter seabed topography, creating pits that may either refill rapidly or potentially cause detrimental impacts for extended periods of time. Immediate losses of infaunal biomass occur and these can affect adjacent areas through food web disturbances at poorly known time scales. If borrow pits are deep, current velocity is reduced at the bottom, which can lead to deposition of fine particulate matter, and in turn, a biological assemblage can be established that is much different in composition than the original. Long-term physical and biological impacts could occur if dredging significantly changes the physiography of shoals.

Dredging causes suspension of sediments, which increases turbidity over the bottom. Although turbidity plumes associated with dredging often are short lived and may affect relatively small areas, resuspension and redispersion of dredged sediments by subsequent currents and waves can propagate dredge-related turbidity for extended periods after dredging ends. For sand dredging from offshore shoals for beach nourishment, turbidity plumes are typically minimal, and consequently turbidity effects are expected to be less important in unprotected offshore areas because sand settles more rapidly than clay and silt and offshore shoals tend to be coarser than inshore deposits. In addition, the open ocean environment provides more dynamic physical oceanographic conditions, which minimize settling effects.

Offshore organisms are adapted to sediment transport processes, which create scouring, natural turbidity, and sedimentation under normal conditions. Biological responses to turbidity depend on all of these physical factors, coupled with the type of organism, geographic locations, and the time of year. Turbidity from dredging can affect food availability for benthic organisms. Changes in light penetration and wavelengths due to turbidity can affect visibility and may be detrimental or beneficial, depending in part on whether an organism is predator or prey. Turbidity can interfere with food gathering processes of filter feeders and organisms that feed by sight as a result of inundation with non-nutritive particles. In addition to altered feeding rates, other biological responses to turbidity include reduced hatching success, slowed growth, abnormal development, tissue abrasion, and increased mortality. Suspension and dispersion processes uncover and displace benthic organisms, temporarily providing extra food for bottom-feeding species.

Suspended sediments settle and are deposited nearby dredged offshore sand borrow sites. The extent of deposition and boundaries of biological impact are dependent on the type and amount of suspended sediments and physical oceanographic characteristics of the area. Deposition of sediments can suffocate and bury benthic biota, although some mobile soft bottom organisms are able to migrate vertically to the new surface. Furthermore, sediment deposition can inhibit larvae of numerous invertebrate species that need hard surfaces to settle and develop.

BIOLOGICAL RESOURCES

Previous reviews concerning potential impacts of offshore sand mining (Research Planning, Inc. et al., 2001) suggested further investigation into the status of sand shoals as EFH for federally managed species and their prey. They found very little data available on the ecological function of sand shoals by fishes or invertebrates. Since the Research Planning, Inc. et al. (2001) report was issued, information regarding fish utilization of sand shoals in the Mid-Atlantic Bight region has emerged, particularly in the region offshore Delaware, Maryland, and New Jersey. Data gathered from individual shoals confirmed that a diverse assemblage of demersal and pelagic fishes associate with regional sand shoals and potentially use these shoals for feeding, spawning, and growing to maturity, often during migrations across the shelf in the fall and spring.

Benthic invertebrates that inhabit sand shoals provide structural fish habitat (worm tubes, burrows, and depressions) as well as a forage base for demersal feeders. Invertebrate species richness is lower on the shoals compared to surrounding areas. Field studies of adult fish species collected with trawl and gill nets confirms that benthic feeders such as skates, scup, drums, searobins, flounders, and black seabass occur around shoals and adjacent sand bottom areas. These species are behaviorally and morphologically adapted for benthic feeding in sedimentary environments.

Pelagic species such as bay anchovy, Atlantic menhaden, Atlantic mackerel, butterfish, and striped bass were also documented to associate with shoals. It is possible that hydrodynamic effects of the shoal features aid in water column feeding by these species. Spawning by fishes in the vicinity of sand shoals can be inferred from the presence of eggs and early stage larvae. Plankton net samples revealed that anchovy, Atlantic menhaden, Atlantic mackerel, and searobins spawn in the vicinity of shoals in the Mid-Atlantic Bight. Shoals may also be important as juvenile habitat for species that utilize both inshore estuarine habitats and the nearshore shelf as nursery areas. The precise nature of any obligate association of demersal or pelagic fishes with shoals is not known, but it appears that many fish species rely on shoal features as a part of a broader, cross-shelf habitat continuum within which they complete their life cycles. EFH evaluations should be made to avoid or minimize any adverse physical and biological effects produced by sand dredging on shoals in OCS waters.

MODELING

Geomorphologic changes associated with potential sand mining scenarios on shoals offshore Fenwick Island, Maryland, were simulated using three interrelated numerical models. Tidal hydrodynamic, wave process, and sediment transport pattern models were coupled to assess the morphologic response of offshore sand shoals to various “dredging” scenarios in support of future beach nourishment requirements. The excavation scenarios simulated were

- Dredging a hole over a designated area on the shoal;
- Dredging the leading edge of a shoal;
- Dredging the trailing edge of a shoal; and
- Dredging in a striped pattern to facilitate recruitment of benthic invertebrates into dredged areas.

Tidal hydrodynamics for the continental shelf and nearshore areas offshore the Delmarva Peninsula were modeled using the Advanced Circulation Model for Oceanic Coastal and Estuarine Waters (ADCIRC). ADCIRC is a two-dimensional (2-D), depth-integrated circulation model. Model prediction of tidal amplitude and phase offshore Ocean City Inlet matched well with measured data from a NOAA tide gage. Average tidal flow velocities observed in the study area are on the order of 0.05 m/s. The direction of flow is observed to be north/northeast on a flooding tide and south/southwest on the ebbing tide.

With such small tidal velocities so far offshore, incident wave energy played a primary role in sediment movement and morphology change at the offshore shoals. Nearshore wave heights and directions across Weaver Shoal, Isle of Wight Shoal, and Shoal A were estimated using the USACE STeady-state spectral WAVE model (STWAVE). STWAVE is a steady state, spectral wave transformation model that uses 2-D (frequency and direction versus energy) spectra as input to simulate wave refraction and shoaling induced by changes in bathymetry and by wave interactions with currents. Hindcast wave data from the USACE Wave Information Study (WIS) were used as input to the wave model.

The primary purpose for ADCIRC and STWAVE modeling was to provide forcing for the CMS-M2D model so that shoal morphology change could be examined. CMS-M2D is a 2-D, depth-integrated, finite-difference hydrodynamic model that has the option of including morphology change estimates through the use of a sediment continuity equation for updating changes in bathymetry. Full coupling with an external wave model (STWAVE in this case) is possible, with the wave model providing radiation and shear stresses to CMS-M2D. In return, the hydrodynamic and morphology changes are passed back to the wave model.

Bathymetric change at and adjacent to the shoals in response to various “dredging” geometries was of particular interest. In addition to a baseline scenario for each of the shoals, three dredging geometries for Weaver and Isle of Wight shoals were simulated, along with two dredging scenarios at Shoal A. Each of these geometries was evaluated under a 3-day storm from the northeast and a 3-day storm from the east. Results from the Baseline scenario provided insight to the current trends in shoal morphology and migration. Simulations indicate dominant sand transport from northeast to southwest and south, where sand is eroded from shoal crests and deposited on the leading edge of the shoal.

Modeling results illustrated that a dredged portion of a shoal will not simply fill because there is a depression present. If dredging is performed on a portion of a shoal that is not active under present conditions, there will be a lack of sand availability to replenish the sand removed during borrow site excavation. Imposed storm conditions will not be effective at mobilizing significant amounts of sand in the excavated area, and larger-scale shelf processes and major storm events may be the only mechanisms by which the "dredged" areas will be filled. Material removed from active areas of a shoal will be replenished more quickly by normal wave conditions at the site. Shallow shoal crests, like Isle of Wight Shoal, and the leading edge of all three shoals are noted as the active areas of erosion/deposition. These active transport and deposition areas will recover to original conditions more rapidly than inactive portions of shoals.

The striped pattern dredging scenario indicated that trenches in excavated areas fill almost uniformly along the length of the "dredged" area. While deposition was greater along the northern edges of excavated trenches, each trough showed deposition for most of its length. Deposition in the center and southern portions of the "dredged" region is a result of sand erosion from undisturbed areas and into adjacent low areas. In terms of timely and uniform recovery of a shoal from borrow site dredging, the striped pattern of sediment removal offers great promise.

QUESTIONS AND ALTERNATIVES

Based on geological models of shoal formation, there does not appear to be a mechanism supporting the idea that the structural integrity of a feature will "deflate" or "unravel" when subject to repeated dredging. As long as a seafloor irregularity remains upon which to reform the ridge, dominant shelf processes will construct these features as described by shelf ridge process models.

For the dredging scenarios examined, the most desirable location or subarea (crest, leading edge, or trailing edge) of a shoal for dredging is the leading edge from a physical standpoint. This is primarily due to net long-term deposition and faster infilling rates of dredged areas. The crest would be a second choice, followed by the trailing edge. In terms of the dredging removal method (cut, slice, or striped pattern) the striped pattern showed the most promise. Shallow striped areas in the modeling scenarios recovered more rapidly toward pre-dredging levels.

Some benthic biological differences are expected to occur along the longitudinal axis of a shoal reflecting physical habitat differences that occur across the feature. The leading edge, crest, and trailing edge may support assemblages that are partially distinct in terms of the occurrence of certain populations. Although they are to some extent variable, these assemblages are expected to show general consistency of population composition longitudinally. There are differences in community patterns comparing the current-facing and lee sides of shoals, in particular the occurrence of aggregations of tube-building populations on the lee side. Benthic biological differences among shoal subareas suggest that additional stratification should be considered when designing dredging projects and monitoring programs.

Targeting shoal and ridge locations that may be less susceptible to prolonged physical alteration assumes in part that the nature of biological recovery, including the speed of colonization and benthic assemblage composition, will depend in large measure on the physical characteristics of a site after dredging. There are other system drivers that may influence differing measures of biological recovery including variability in supply, transport, and settlement of larvae for some species on a spatial scale that greatly exceeds the shoal area itself.

RECOMMENDATIONS

For a given dredging and beach nourishment interval, it is advisable to remove only a portion of a particular ridge or shoal. For a given ridge or shoal, project elements such as target site location, dredging depth, and excavation patterns may be designed to avoid persistent physical alteration after cessation of dredging. Recommendations for selection of target sites and dredging methods to avoid or minimize adverse physical consequences may include:

- Extracting sand from a depocenter, leading edge, or downdrift margin of a shoal, to avoid interrupting natural shoal migration and potentially reduce the time required for site refilling;
- Avoid dredging in erosional areas that source downdrift depocenters, which also may be slow to refill after dredging;
- Shallow dredging over large areas rather than excavating small but deep pits may be preferred depending on the infaunal charactersitics;
- Dredging in a striped pattern to leave sediment sources adjacent to and interspersed throughout target areas, leading to a more uniformly distributed infilling process; and
- Excavation should occur on shoal crests and higher areas of the leading edge rather than lower areas of the shoals because of greater exposure to wave-generated turbulence and greater sediment mobility, which potentially results in more rapid sediment reworking and site infilling, and likely would induce the benthic community to recover more rapidly.

Shoals and ridges serve as a benthic nursery area, refuge, and feeding sites for a variety of ecologically important and commercially and recreationally harvested fish and invertebrate resources. In assessing the consequences of sand mining on EFH of shoal and ridge systems of the Federal OCS, a thorough analysis should include an assessment of how different techniques of dredging could affect fishery resources and site-specific investigations of physical environmental processes in addition to species life history information and patterns of habitat use. EFH analysis also should include assessment of the level of importance of geomorphological and hydrodynamic flow regimes with respect to fishery resources.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS
(Continued)

Page

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES
(Continued)

Figure **Page**

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES
(Continued)

Table **Page**

LIST OF ACRONYMS

2-D	two-dimensional
2G	second generation
3-D	three-dimensional
3G	third generation
ADCIRC	Advanced Circulation Model for Oceanic Coastal and Estuarine Waters
ANOVA	analysis of variance
ASMFC	Atlantic States Marine Fishery Commission
CFR	Code of Federal Regulations
CSA	CSA International, Inc.
CSH	cross-shelf habitat
DGPS	differential global positioning system
EFH	essential fish habitat
ESA	Endangered Species Act
FMP	Fishery Management Plan
GPS	global positioning system
HAPC	Habitat Areas of Particular Concern
HMS	Highly Migratory Species
MAFMC	Mid-Atlantic Fishery Management Council
Mcy	million cubic yards
MEC	munitions and explosives of concern
MGS	Maryland Geological Survey
MHW	mean high water
MLW	mean low water
MMS	Minerals Management Service
MSL	mean sea level
NAVD 88	North American Vertical Datum of 1988
NDBC	National Data Buoy Center
NEFMC	New England Fishery Management Council
NEPA	National Environmental Policy Act
NGVD	National Geodetic Vertical Datum
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
OCS	Outer Continental Shelf
SAV	submerged aquatic vegetation
SIMPER	similarity percentage breakdown
STWAVE	Steady-state Spectral WAVE Model
TED	turtle-excluding device
UXO	unexploded ordnance
USACE	U.S. Army Corps of Engineers
VIMS	Virginia Institute of Marine Science
WIS	Wave Information Study

1.0 INTRODUCTION

The Federal Outer Continental Shelf (OCS) contains large sand deposits that are expected to serve as long-term sources of borrow material for beach nourishment and coastal restoration projects. Potential for exploitation of these resources has grown rapidly in the last several years with identification of suitable sand resource areas in some OCS regions. Demand for high quality sand suitable for beach nourishment, coastal protection, and other public and private projects is anticipated to increase during coming years.

Considering future beach nourishment needs, renourishment maintenance cycles, and anticipated storms, coastal jurisdictions recently have become more interested in sand resources seaward of State waters for several reasons. There is increasing awareness that sand is a valuable resource and should be carefully managed as such. Onshore sources of suitable sand that were once abundant are becoming scarce due to deposit depletion, competing uses, and urban development. For ambitious nourishment projects, transporting sand from nearshore areas often is far more economical than trucking sand from upland sources. Like onshore sources, nearshore sand resources often are limited, diminishing in supply, and/or polluted, necessitating the need for alternative deposits that exist farther offshore. Using offshore deposits provides the important benefit of adding sand to the beach/nearshore system, rather than simply moving sand from one part of the system (nearshore) to another (beach). Furthermore, sand resources in Federal waters may be environmentally preferable due to concerns that extraction of large quantities of sand and gravel from nearshore sites can change the bathymetry of an area and result in modifications to existing physical oceanographic conditions. In relatively shallow nearshore waters, alterations to local current and wave regimes can have drastic consequences in terms of erosion and accretion. From a biological standpoint, excavation of sand resource areas farther from the shoreline may prove to have less adverse impacts on essential fish habitat (EFH) than sites closer to shore (Jordan, 1999).

The Minerals Management Service (MMS) is responsible for managing exploration and development of mineral resources on submerged Federal OCS lands. Among MMS missions is the need to develop approaches for managing the nation's OCS mineral resources in an environmentally sound and safe manner. Anticipating that requests for sand will increase significantly due to beach nourishment and storm protection needs, the MMS Sand and Gravel Program is ensuring that environmental management processes will be expedited when OCS sand resources are most needed. MMS has authority to convey rights to OCS sand, gravel, or shell resources for shore protection, beach or wetland restoration projects, or construction projects funded in whole or part or authorized by the Federal Government. To further enhance and meet its missions, the MMS Sand and Gravel Program funded the project titled "Analysis of Potential Biological and Physical Impacts of Dredging on Offshore Ridge and Shoal Features." This document is the Technical Report for the project.

1.1 OFFSHORE RIDGES AND SHOALS

Increased demand for beach quality sand from continental shelves fronting the east and Gulf coasts of the United States has resulted in numerous geological investigations documenting the location of potential sand resource areas, sedimentologic characteristics of deposits, and the quantity of sand available in State and Federal waters (e.g., Conkwright et al., 2000; U.S. Army Corps of Engineers [USACE], 2008). Most studies have focused on continental shelf sand ridges because ridge/shoal features have been identified as a primary source of quality beach sand. Shelf ridges are constructive features developed and maintained by modern wave and current processes (Huthnance, 1982; Hulscher et al., 1993) in areas of sufficient sand supply in a transgressive setting (Snedden and Dalrymple, 1999). Along the mid-Atlantic inner continental shelf, Field and Duane (1976), Field (1980), Swift and Field (1981), McBride and Moslow (1991), Snedden et al. (1994), Conkwright et al. (2000), USACE (2008), and many others document the occurrence and formation of sand ridges and swales similar to those shown in **Figure 1.1**. Extensive ridge and swale deposits in the northeastern Gulf of Mexico (east of Mobile Pass on the Alabama and northwest Florida continental shelf; **Figure 1.2**) have been described by Parker et al. (1992), McBride and Byrnes (1995), Parker et al. (1997), McBride et al. (1999), and Byrnes et al. (2004). In all shelf ridge settings, the long axis of ridges and swales are oriented in the direction of predominant storm wave approach (Hayes and Nairn, 2004). Storm waves generally approach from the southeast in the northeastern Gulf of Mexico and from the northeast in the Mid-Atlantic Bight, indicating a link between storm wave and current processes and shoal formation/maintenance (Snedden and Dalrymple, 1999).

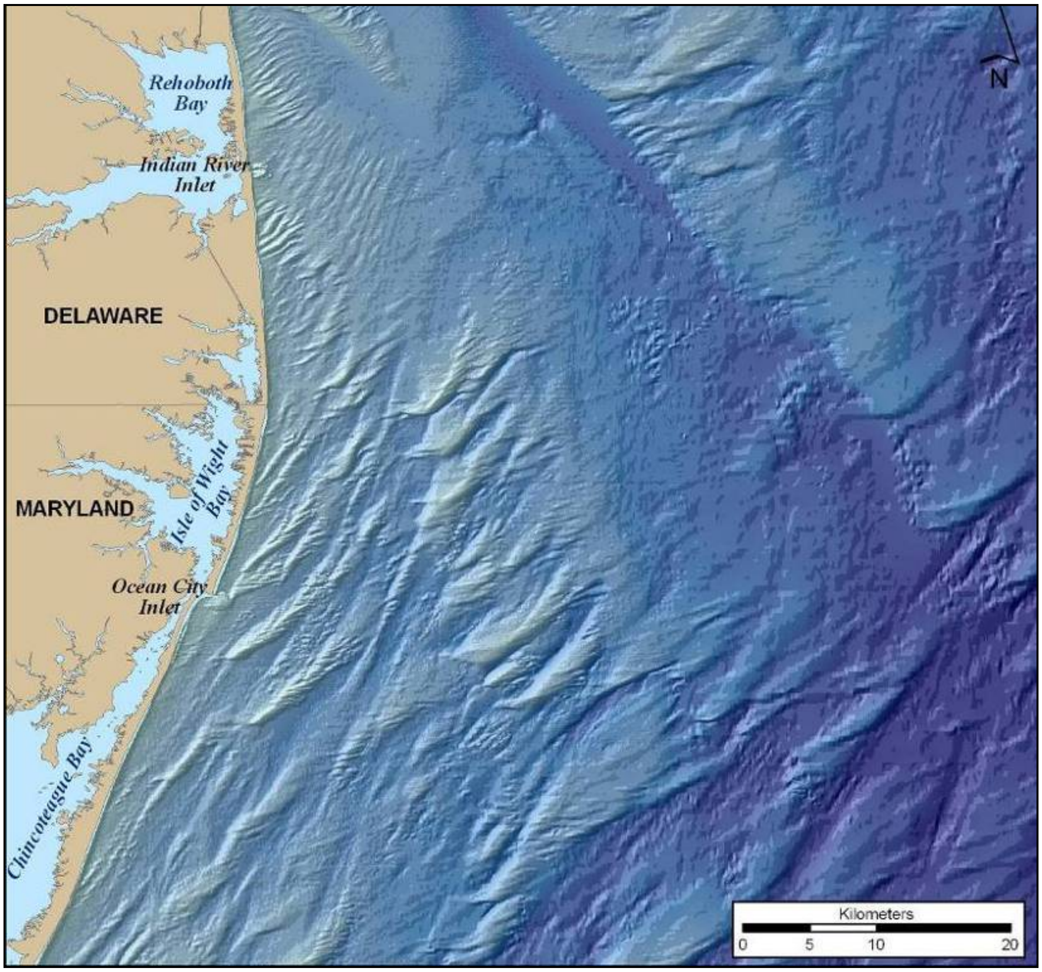


Figure 1.1. Illustration of ridge and swale topography on the mid-Atlantic continental shelf, Maryland, and Delaware.

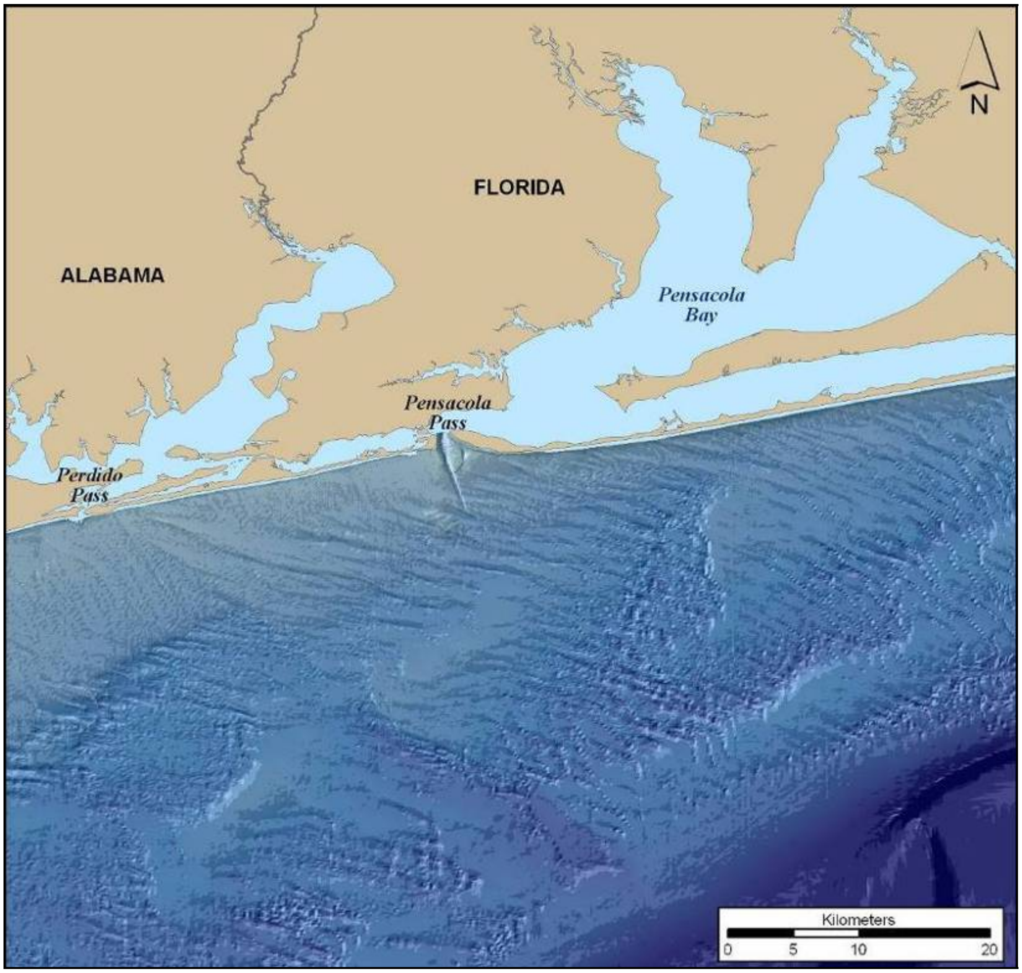


Figure 1.2. Illustration of ridge and swale topography on the west Florida continental shelf, seaward of Pensacola Pass.

In the early 1970’s, offshore sand resources became an important component of USACE projects that focused on beach nourishment for coastal erosion control. Numerous sand resource studies were completed by USACE research scientists and other researchers during the 1970's and 1980’s to better understand shelf sediment transport processes and patterns on the Atlantic inner continental shelf (e.g., Swift et al., 1972). Duane et al. (1972) studied approximately 200 shoals at least 910 m long and 3 m in relief to document the characteristics of shelf linear sand ridges between Long Island (New York) and Florida. Swift and Field (1981) documented geomorphic characteristics of shoreface-attached, nearshore-detached, and offshore-detached sand ridges for the best developed ridge and swale topography in the Mid-Atlantic Bight. Shoreface ridges extend from the shoreface in water depths as shallow as 3 m at an oblique angle. Ridge side slopes average about 1.5º, and they are generally symmetrical (Swift and Field, 1981).

Nearshore-detached sand ridges are generally more massive than shoreface-attached and have smooth, single-crested southern ends. The average seaward slope of the ridges is about two times as steep as the average landward slope; however, both slopes are less than those associated with shoreface ridges (Swift and Field, 1981). Furthermore, the highest point on ridges occurs toward the southern end of the shoal before decreasing abruptly to the ambient shelf surface. Offshore-detached sand ridges are similar to nearshore ridges except they are typically less elongate and have greater cross-sectional areas and seaward slopes many times steeper than landward flanks (Swift and Field, 1981). USACE (2008) provided a summary of shoal characteristics derived from Swift and Field (1981) documenting geomorphic differences among the three categories of continental shelf sand ridges (**Table 1.1**).

Table 1.1. Geometric characteristics of continental shelf sand ridges offshore Maryland and Delaware (Swift and Field, 1981).

Geomorphic Characteristics of Continental Shelf Sand Ridges	Shoal Type		
	Shoreface-Attached	Nearshore-Detached	Offshore-Detached
Shape	Linear	Linear	Comma
Ambient water depth (m)	>3	<12	>12
Mean slope	1.5º	1.0º	0.5º
Steepest slope	2.5º	2.0º	7.0º
Steepest flank	Landward	Seaward	Seaward
Mean asymmetry (landward : seaward slope)	1:1	1:2	1:5
Mean aspect ratio (length : width)	9:1	6:1	3:1
Maximum cross sectional area (x 103 m^2)	87	187	4,481

Shelf sand ridges are common along the Atlantic and Gulf coasts of the United States. However, considerable variability in geomorphic and sedimentologic characteristics exists as a function of sediment source and dominant wave and current processes. Snedden and Dalrymple (1999) presented a comprehensive analysis of shelf sand ridge formation and evolution and proposed a unified conceptual model of ridge origin and evolution that encompasses ridge variability. The conceptual model consisted of three components: 1) formation of an initial irregularity on the shelf surface upon which modern ridges develop; 2) the interaction of storm and shelf-current processes in the presence of the initial seafloor irregularity to form and maintain the modern sand ridge (described by Huthnance [1982] and Hulscher et al. [1993]); and 3) subsequent ridge evolution in response to modern wave and current processes.

Hayes and Nairn (2004) reviewed the natural maintenance of sand ridges on continental shelves relative to potential offshore sand mining on these ridges. They recognized the value of the Huthnance model for describing the evolution of tidal sand ridges; however, it was emphasized that the following primary constraints had to be met for the model to predict properly: 1) a sufficient quantity of sand; 2) currents capable of moving the sand; and 3) a pre-existing seafloor irregularity. For storm-dominated shelves, Trowbridge (1995) proposed that southerly currents generated by northeast storm waves would produce the same response on sand ridges as asymmetrical tidal currents imposed by Huthnance (1982). Although limitations exist with all sand ridge evolution theories, Snedden and Dalrymple (1999) used various geological data sets to develop an evolutionary progression of sand ridges on continental shelves (**Figure 1.3**). The process by which this progression occurs is described by Snedden et al. (1999).

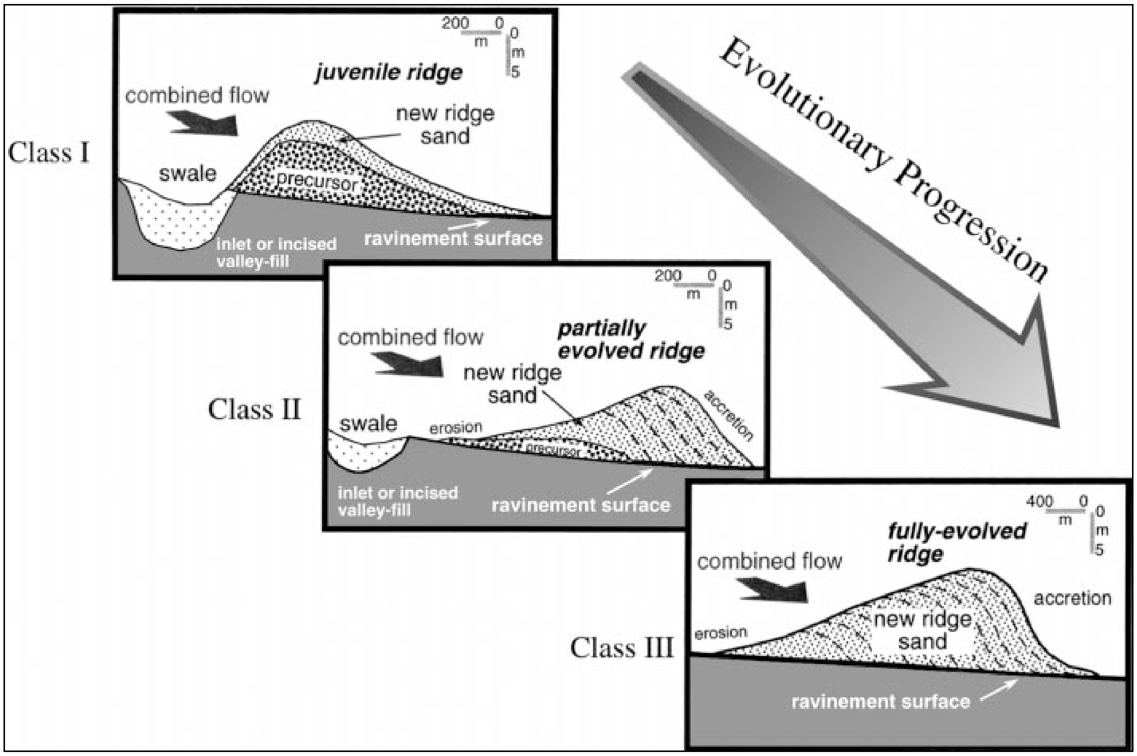


Figure 1.3. Schematic diagram of ridge classes as presented in Snedden and Dalrymple (1999). The precursor in the case of the Class I and II ridges is a pre-existing bathymetric feature, sometimes associated with a shoreline or inlet, which provides the focal point for the ridge growth and migration via the Huthnance process. Subsequently, this precursor may be removed or reduced in size through current erosion and ridge migration. Accretion on the landward side of the juvenile ridge (Class I) is largely induced by fair-weather wave transport from the ridge crest and is not expected to occur in ridges developed in deeper water, as with Classes II and III. New ridge sand is primarily deposited in shelf waters by combined flows associated with storms.

Recognizing that shelf sand ridges are modern constructive features that form and migrate in response to dominant coastal processes, scientists and engineers have identified these deposits as primary resource targets for beach nourishment and coastal restoration. Numerous site-specific environmental studies have been completed for Federal and State agencies responsible for managing sand resources on the continental shelf (e.g., Drucker et al., 2004) to evaluate the potential effects of sand mining from offshore shoals on local and regional sand transport patterns. In all studies where changes in wave and current processes were evaluated relative to sand mining on offshore shoals, there have been no significant changes in regional sand transport patterns (e.g., Byrnes et al., 2004; Maa et al., 2004).

Hayes and Nairn (2004) indicate that the direct influence of wave action has received little attention with regards to the maintenance and migration of shelf ridge and swale features. They applied a Boussinesq wave model using a wave representative of northeast storm conditions to simulate irregular multidirectional waves that included partial reflection and current interaction. The simulation illustrated refraction over Fenwick Shoal that created wave convergence on the shoal crest. It was suggested that wave convergence on the shoal crest may be a primary factor for maintaining shoals aligned with the dominant wave direction (Hayes and Nairn, 2004). Furthermore, because converging waves exist on the shoal crest, convergence of sand transport likely occurs on the crest as well.

Although consensus does not appear to exist regarding dominant processes responsible for ridge evolution and maintenance, the formation and maintenance processes described by Huthnance (1982), Trowbridge (1995), and Hayes and Nairn (2004) can explain shoal morphodynamics and sediment transport mechanics for most, if not all, shelf sand ridges. In every case, these features are depositional, and many migrate in response to dominant coastal processes. The shallower the ridge, the more likely wave processes will control morphodynamics. Where shelf currents overwhelm wave-induced currents responsible for sand transport and ridge maintenance, shoal evolution may be best described by Huthnance (1982). When wave-driven flow is dominant, convergence at ridge crests may be best described by Hayes and Nairn (2004). Either way, as long as an initial seafloor irregularity is present on the shelf upon which waves and currents can mold and create shelf ridges, these features will continue to grow and migrate providing regional shelf transport processes are maintained.

1.2 STUDY OBJECTIVE AND QUESTIONS

The MMS specified the study objective and posed questions to be addressed during the project. The objective of the study was to examine and evaluate potential biological and physical effects of offshore dredging within ridge and swale features on the Federal OCS and to suggest engineering options and mitigation measures that can be implemented to avoid potential deleterious impacts, while allowing for the selective removal of needed sand volumes for nearby beach projects. To address this objective, the MMS requested that a program be developed to address biological and physical issues associated with the long-term use of offshore sand ridges as a source of sand borrow material for beach and coastal restoration efforts and suggest engineering options/dredging techniques to allow for the selective removal of sand for beach restoration and nourishment projects. Specifically, the MMS posed the following four questions relative to continued use of offshore submerged shoals and the ridge and swale features that occur on the OCS. These questions were incorporated into the technical approach discussed in **Section 1.3.1**. These questions originated and were discussed as information gaps during an MMS-funded study (Research Planning, Inc. et al., 2001) conducted prior to the present study.

- What is the use and role of sand ridges and shoals as potential EFH by migrating or resident fish? (**Figure 1.4**, Boxes 3 and 8; see **Section 4.0**).
- Is there a preferred manner to remove sand from a shoal/ridge feature to maximize its use and maintain the integrity of the feature? (**Figure 1.4**, Boxes 5, 6, and 8; see **Section 6.1**).
- Are there benthic biological differences that run longitudinally along the ridge and shoal features such that dredging operations should be tailored to avoid certain areas? (**Figure 1.4**, Boxes 4 and 8; see **Section 6.2**).
- Are there procedures to dredge shoal and ridge features that will minimize ecological impacts and/or speed recovery, such as completely dredging one specific shoal or ridge and leaving adjacent features untouched versus dredging a small amount of sand from each shoal or ridge feature, or dredging in strips, leaving undisturbed areas that act as local sources of recruitment and allow recruitment from older life stages? (**Figure 1.4**, Boxes 2, 5, and 8; see **Section 6.3**).

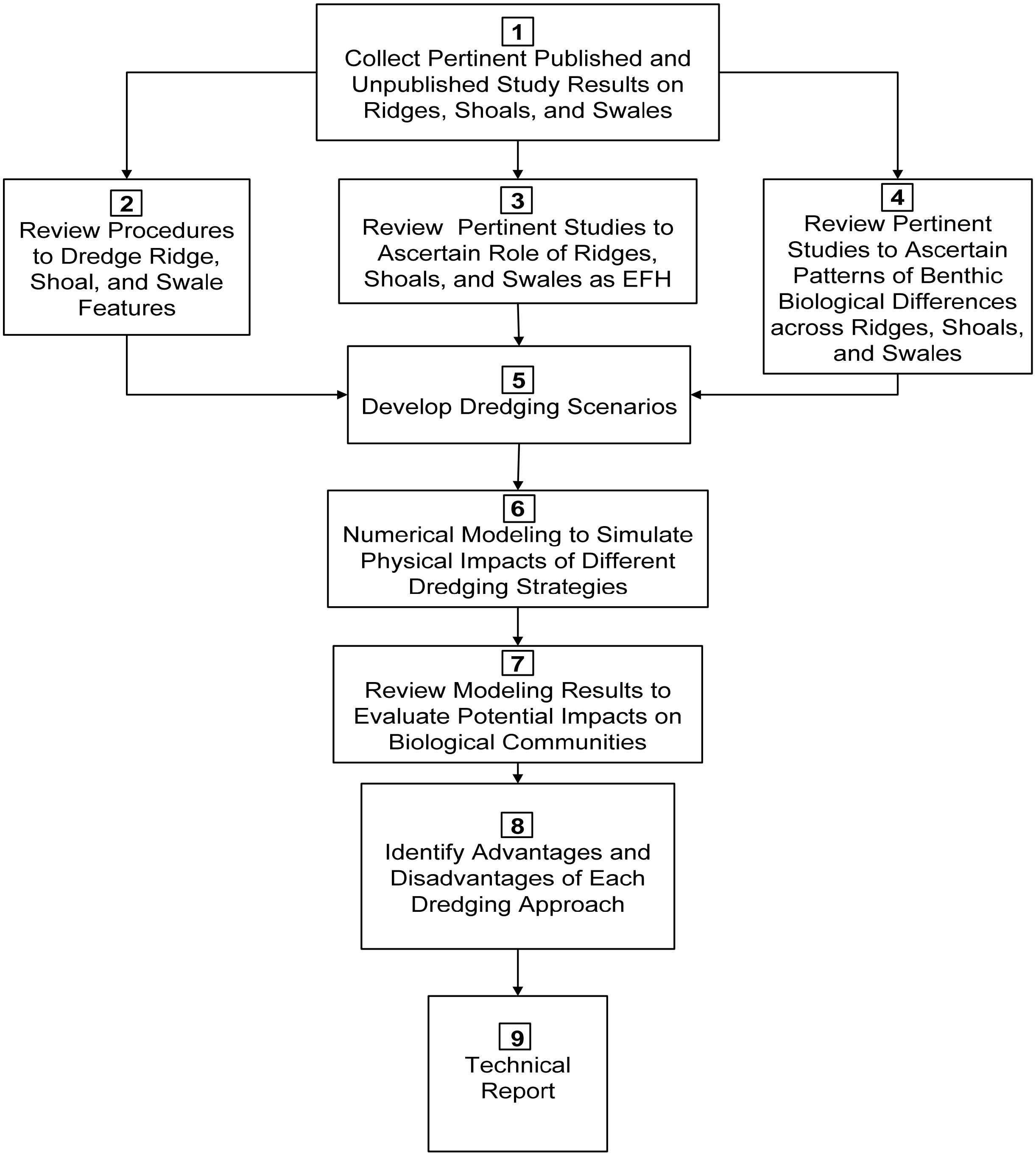


Figure 1.4. Flowchart of technical approach.

1.3 STUDY DESIGN

1.3.1 Technical Approach

To accomplish the study objective, a technical approach consisting of nine steps was developed (**Figure 1.4)**. The first step of the technical approach was to collect pertinent published and unpublished study results on ridges, shoals, and swales (**Figure 1.4**, Box 1). Information was collected from author libraries, other private and public libraries, and internet websites.

The second step was to review procedures to dredge ridge, shoal, and swale features (**Figure 1.4**, Box 2). The review included cutterhead dredges, hopper dredges, and other offshore dredging equipment and techniques as described in **Section 2.0**.

The third and fourth steps concerned biological tasks. The third step was to review pertinent studies to ascertain the role of ridges, shoals, and swales as EFH (**Figure 1.4**, Box 3). To adequately address the third step, a cross-shelf framework was used (**Section 4.6**). The fourth step was to review pertinent studies to ascertain patterns of benthic biological differences across ridges, shoals, and swales (**Figure 1.4**, Box 4). The results of the third and fourth steps are presented in **Section 4.0**.

The cross-shelf approach was chosen because EFH is broadly defined as "those waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity," which covers the full spectrum of life histories and habitats rather than only ridges, shoals, and swales. The EFH definition demands considerations of life histories and estuarine to shelf habitats. Considering only ridges, shoals, and swales is too myopic compared to the preferable cross-shelf matrix approach. To fully understand the role and use of ridges, shoals, and swales by resident and migratory fishes, a broader scale approach is needed. The cross-shelf matrix enables identification of the wide variety of habitats where various life stages occur. The cross-shelf approach also helps identify which species are true residents and which species are actually migratory. Important migrations are not only broad-scale coastal movements but also developmental, ranging from inshore nursery to offshore adult habitats. Some species and life stages may be very general in their habitat requirements, whereas others may prove to be highly dependent on ridges and shoals. For example, if juvenile fishes of a particular species occur only on shoals and not in estuaries, inlets, and other inner and outer shelf habitats, then a statement can be made based on the cross-shelf matrix that shoals are EFH for that particular species and life stage. Such findings will not be readily apparent if ridges and shoals are considered in isolation from the surrounding habitats. The cross-shelf approach provides a proactive assessment of EFH, uncovering habitat connectivity of individual species life history stages within the region. The cross-shelf matrix provides a tool that can be used along the East and Gulf Coasts to properly determine if shoals and swales are truly EFH and helps to answer the question "What is the use and role of sand ridges and shoals as potential EFH by migrating or resident fish?"

The fifth step was to develop dredging scenarios (**Figure 1.4**, Box 5). Existing knowledge of borrow site geometries was considered relative to environmental and economic considerations. Equipment and techniques available under existing and emerging technologies also were evaluated. Dredging scenarios were then designed to include the natural, long-term evolution of the shoal. Some potential dredging scenarios specified by the MMS and considered at the beginning of the project were as follows:

- Dredging completely one specific ridge or shoal and leaving adjacent features untouched;
- Dredging a small amount of sand from each shoal or ridge feature; and
- Dredging in strips, leaving undisturbed areas that act as local sources of recruitment and allow recruitment from older life stages.

These and other dredging scenarios were considered during the project as discussed in **Section 5.1.2**.

The sixth step was to conduct numerical modeling to simulate physical impacts of different dredging strategies (**Figure 1.4**, Box 6). The purpose of the modeling approach was to provide baseline information on potential physical impacts, and to evaluate the physical impact producing factors (i.e., sediment removal, suspension/dispersion [turbidity], deposition [changes in sediment thickness and grain size], and other potential physical disturbances from dredging and positioning equipment) such that modeling results could be used to provide statements concerning potential biological impacts of dredging offshore ridge and shoal features. Emphasis was placed on estimating the physical impact producing factors associated with selected dredging scenarios that could be applicable to evaluating near-field and far-field, and short-term and long-term biological impacts.

The seventh step was to review modeling results to evaluate potential impacts on biological communities (**Figure 1.4**, Box 7). Based on the results of the sixth step, modeling results concerning the physical impact producing factors (i.e., sediment removal, suspension/dispersion [turbidity], deposition [changes in sediment thickness and grain size], and other potential physical disturbances from dredging and positioning equipment) were used to base statements concerning potential biological impacts of dredging offshore ridge and shoal features. Biological statements are presented in **Sections 6.2** and **6.3**.

The eighth step was to discuss the advantages and disadvantages of each dredging approach (**Figure 1.4**, Box 8). During discussions, results relative to the relationship between dredging technologies and potential physical and biological impacts were assessed. Comparisons were made of the selected dredging alternatives, and dredging options and mitigation measures were recommended as presented in **Section 7.0**.

The ninth step was to produce the Technical Report (**Figure 1.4**, Box 9). This document is the Technical Report, and its organization is described in **Section 1.4**.

1.3.2 Study Area

The study area encompasses three primary sand shoals in Federal waters offshore the ocean shoreline of Maryland. Maryland's coast is comprised of Fenwick and Assateague Islands. The northern end of Fenwick Island is connected to mainland Delaware, and the southern end of Assateague Island extends into Virginia. Ocean City is situated at the southern tip of Fenwick Island, just north of Ocean City Inlet (**Figure 1.5**).

Figure 1.5. U.S. mid-Atlantic coast, showing the location of Ocean City, Md., and surrounding states.

The continental shelf in this area extends from the Ocean City shoreline seaward about 120 km. The seafloor of the shelf slopes gently seaward to its eastern edge, where water depths are approximately 200 m. Shelf sediments are derived from deposition and erosion of sediments along the continental margin. They include gravel, sand, silt, and clay, as well as seashells and plant remains, and are mainly unconsolidated. These sediments have been reworked by waves and currents accompanied by the rise and fall of sea level. Beaches within the study area currently are experiencing a rise in sea level of about 3 mm per year (National Oceanic and

Atmospheric Administration [NOAA], 2001). Shelf geomorphology is mostly flat but contains a large number of nearshore and offshore sand shoals (**Figure 1.6**). These shoals have been studied by many academic scientists as well as the MMS, USACE, and Maryland Geological Survey (MGS). Studies have evaluated the shoals as potential sources of sand for beach nourishment on Fenwick and Assateague Islands. MGS studied 22 large shoals off the Maryland coast, and Swift and Field (1981) identified 35 large shoals in the study area.

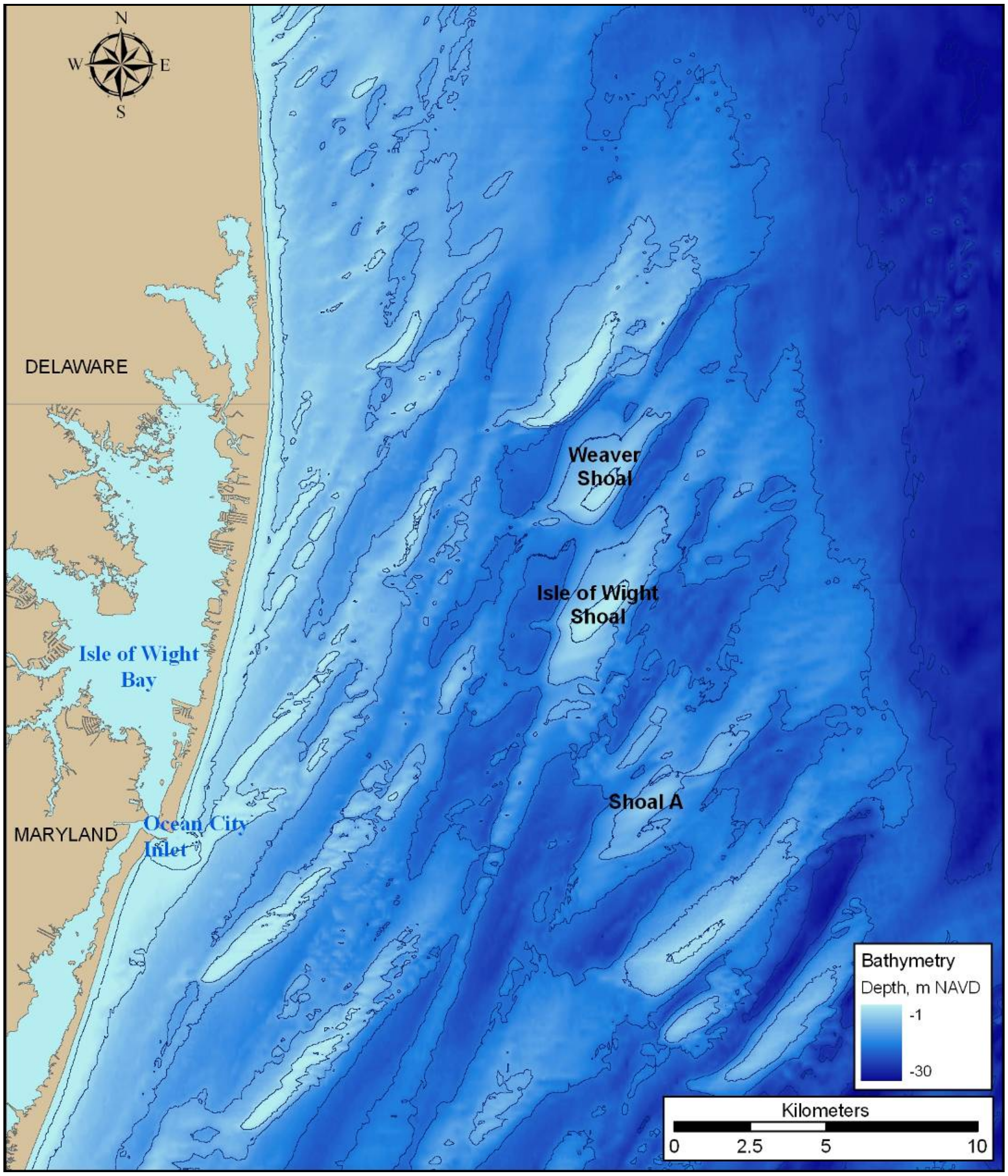


Figure 1.6. Bathymetric map of the study area, documenting three offshore shoals evaluated for potential sand mining for Ocean City, Md., beach nourishment.

Shoreface shoals located offshore Fenwick and Assateague Islands primarily have long axes with a southwest/northeast orientation. Shoal morphology data compiled by MGS show that shoal crests and base water depths gradually increase offshore (USACE, 2008). Shoals range from 1.8 to 27.2 km^2 in area, 3.2 to 11.3 km in length, and 1 to 4 km in maximum width.

Seafloor relief ranges from 7.6 to 15.2 m, and side slopes range from 0.2° to 7.0°. Shoals with larger volumes typically have greater area and relief. The surface of shoals, as well as the surrounding seafloor, often contains smaller scale geomorphic features such as flat plane beds, ripples, and sand waves.

McBride and Moslow (1991), Snedden et al. (1994), and McBride et al. (1999) indicate that nearshore and offshore shoals are most likely formed concomitant with the development and migration of inlets and ebb-tidal shoals. Over the last several thousand years, sea level has risen and caused ebb shoals to detach from the shore and change independently from the retreating shoreline. As water deepened, shoals were less affected by fair-weather waves and continued to migrate and gradually increase in cross-sectional area. This increase in area was accompanied by decreased length to width ratio and grain-size increases on the shoal crest. Storm waves originating from the northeast caused the southwest/northeast alignment of a majority of the shoals. MGS studies in two borrow areas found shoals to migrate south at a rate of 4.5 to 9 m per year, whereas Swift and Field (1981) found that the larger shoals typically migrate to the southeast at rates of 2 to 120 m per year.

Shoals and intershoal regions are predominantly composed of fine to coarse well-sorted sand that is highly variable in thickness and areal extent. As shoals migrate and sand is reworked, coarser sediment becomes concentrated in areas of greatest wave and current energies, typically located along the crests of shoals. The crests contain very little shell material. Shoal flanks are composed of sand and some shell and biogenic material. Intershoal sands contain the most biogenic material, but it is never abundant. Wave and current energies prevent mud from being deposited in the area. Existing mud and fine sand from underlying deposits are often locally exposed on the seafloor. Sand deposits in these areas are usually only a few meters thick and have an overall grain size smaller than that of shoals and mainland beaches.

The study area was selected based on near-term need for sand resources, availability of geological data and previous studies describing shelf sand ridges in the area, and the availability of associated biological resource data and studies. The shoal field offshore the northern Maryland coast was an ideal selection because all of the above criteria were met. The Atlantic Coast of Maryland Shoreline Protection Project reevaluation study (USACE, 2008) identified nine offshore sand shoals as potential sources for beach replenishment material. Geological investigations of these shoals were completed by Conkwright and Williams (1996) and Conkwright et al. (2000). Based on analysis of geological data, biological considerations, geographic location, and concerns regarding unexploded ordnance, USACE (2008) selected four shoals for detailed evaluation as potential sources of sand to meet beach nourishment needs at Ocean City, Md. From these selected shoals, the CSA International, Inc. (CSA) study team chose to evaluate the potential physical and biological impacts of sand mining on Weaver Shoal, Isle of Wight Shoal, and Shoal A (**Figure 1.6**) using hydrodynamic, wave, and sediment transport modeling tools, and existing biological data (e.g., Slacum et al., 2006) to address the questions described in **Section 1.2**.

These three potential borrow areas were evaluated by obtaining sand samples collected from vibracores and grab samples. Patterns of grain size distribution determined from these analyses are displayed in **Figures 1.7**, **1.8**, and **1.9**. Sand borrow area maps were created by USACE and superimposed on the 2002 bathymetry surface. Ideally, sand source grain size should be similar to that of beach sand currently present at the site of beach nourishment. Prior to regular beach nourishment that began in 1988, Ocean City beach sand had a mean grain size of 0.6 mm (USACE, 1989). After several beach fills using offshore sand, mean grain size in 1993 was 0.43 mm (USACE, 2008).

Weaver Shoal is the most northern shoal to evaluate. The mapped area is approximately 4 km long and 2 km wide. Vibracore sample analysis identified two parts of the shoal that contain acceptable sand for beach nourishment: the crest and leading edge and the northern half of the trailing edge. Isle of Wight Shoal is located 4 km to the southwest of Weaver Shoal. It is 6.5 km long and 2 km wide. Sand samples from this feature revealed the southeastern part of the trailing edge and the crest of the shoal to contain sand acceptable for beach nourishment. Shoal A is located 6.5 km to the southeast of Isle of Wight Shoal. The mapped area is 5 km long and 1.5 km wide. Vibracore samples extracted from the shoal identified only the southern two-thirds of the trailing edge of the shoal to be compatible with beach sand on Fenwick Island.

1.4 DOCUMENT ORGANIZATION

This document is organized into eight major sections:

- Section 1.0 – Introduction;
- Section 2.0 – Offshore Dredging Procedures at Ridges and Shoals – Offshore Dredging Equipment and Techniques;
- Section 3.0 – Physical Impact Producing Factors Associated with Sand Mining on Shoals Offshore Maryland;
- Section 4.0 – Evaluation of Biological Resources Associated with Shoals Offshore Maryland;
- Section 5.0 – Selection of Alternative Scenarios and Simulation of Physical Processes;
- Section 6.0 – Questions and Alternatives for Optimizing Physical-Biological Impacts of Shoal Dredging;
- Section 7.0 – Recommendations for Engineering Options and Mitigation Measures; and
- Section 8.0 – Literature Cited.

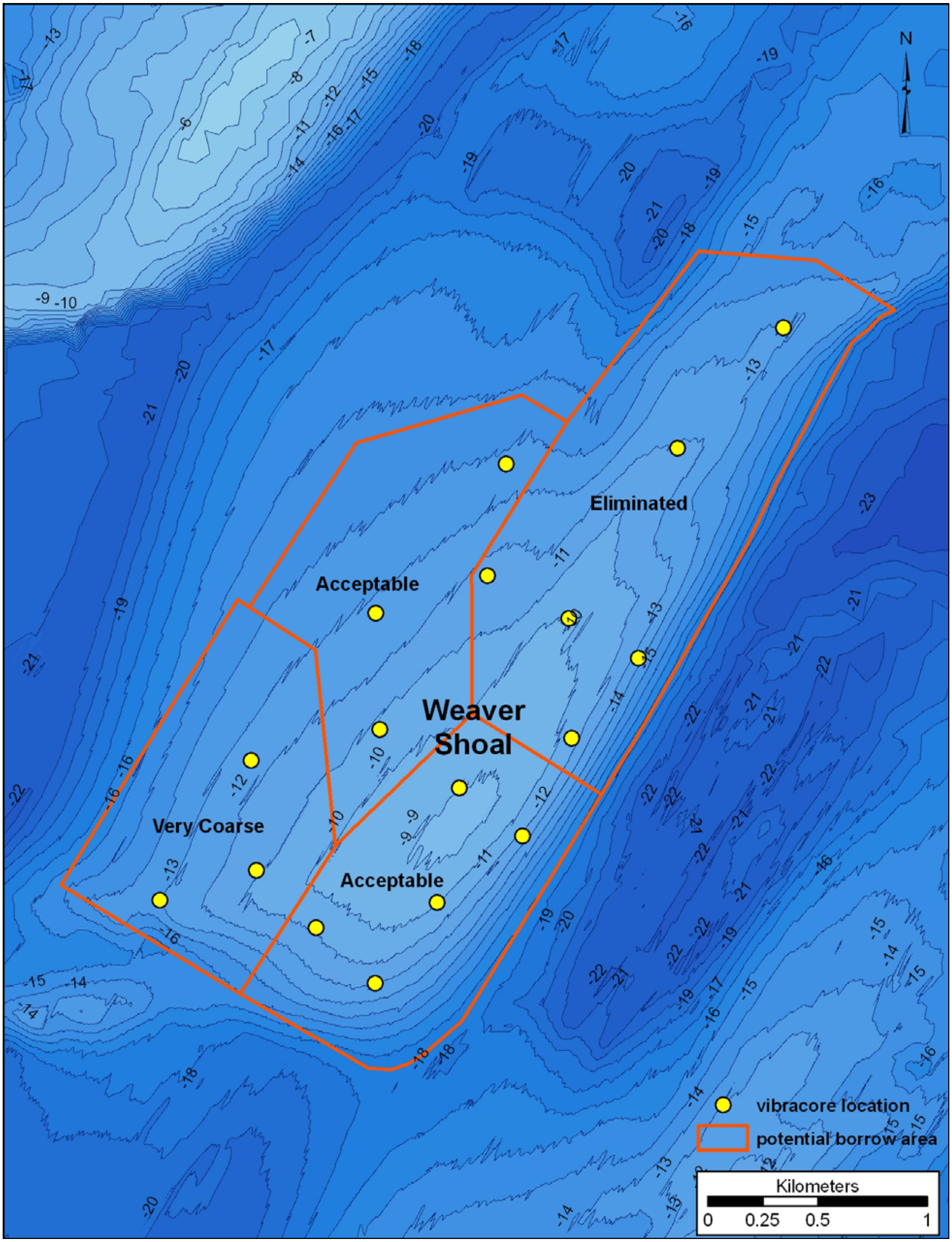


Figure 1.7. Weaver Shoal sand resource acceptability classification by USACE (2008).

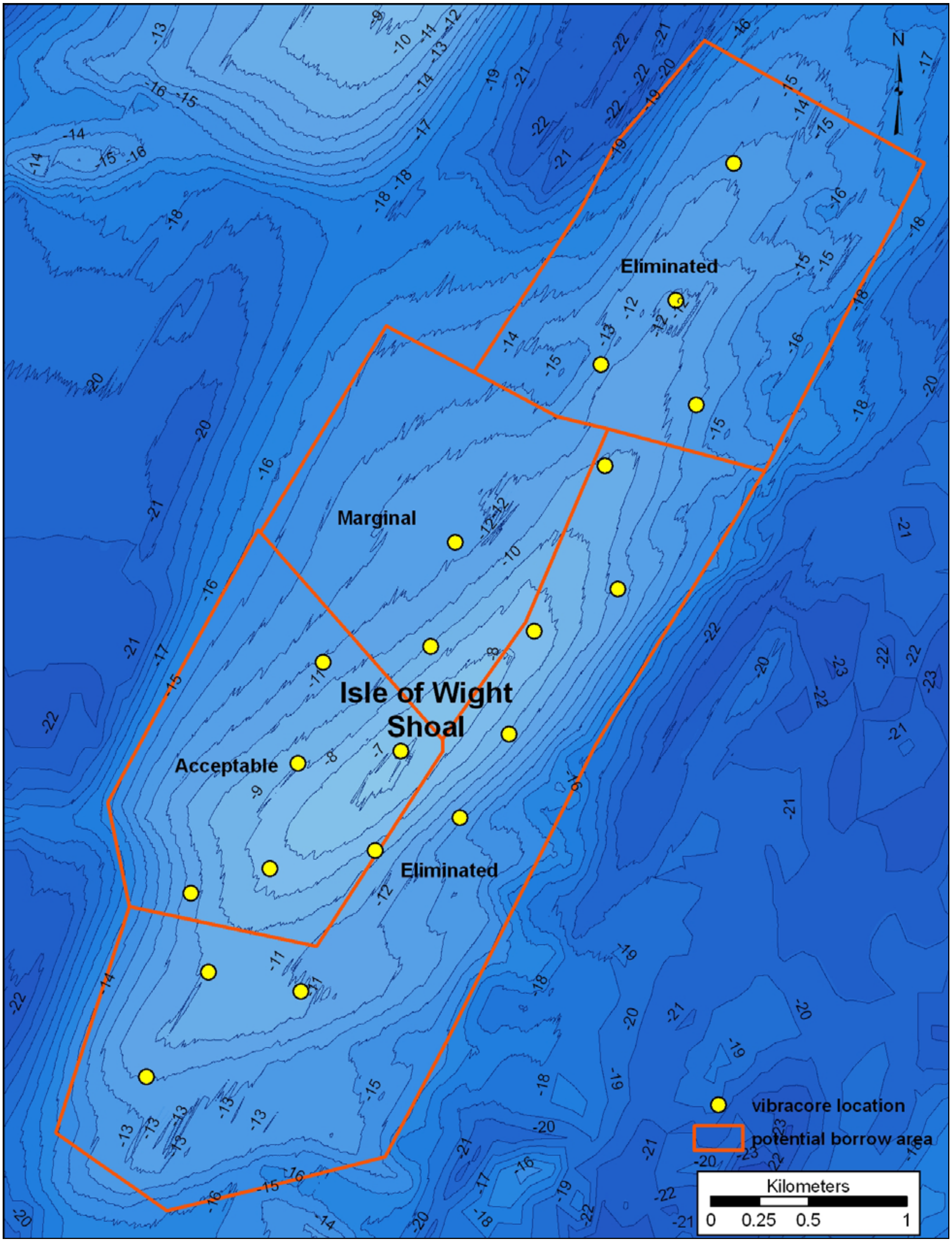


Figure 1.8. Isle of Wight Shoal sand resource acceptability classification by USACE (2008).

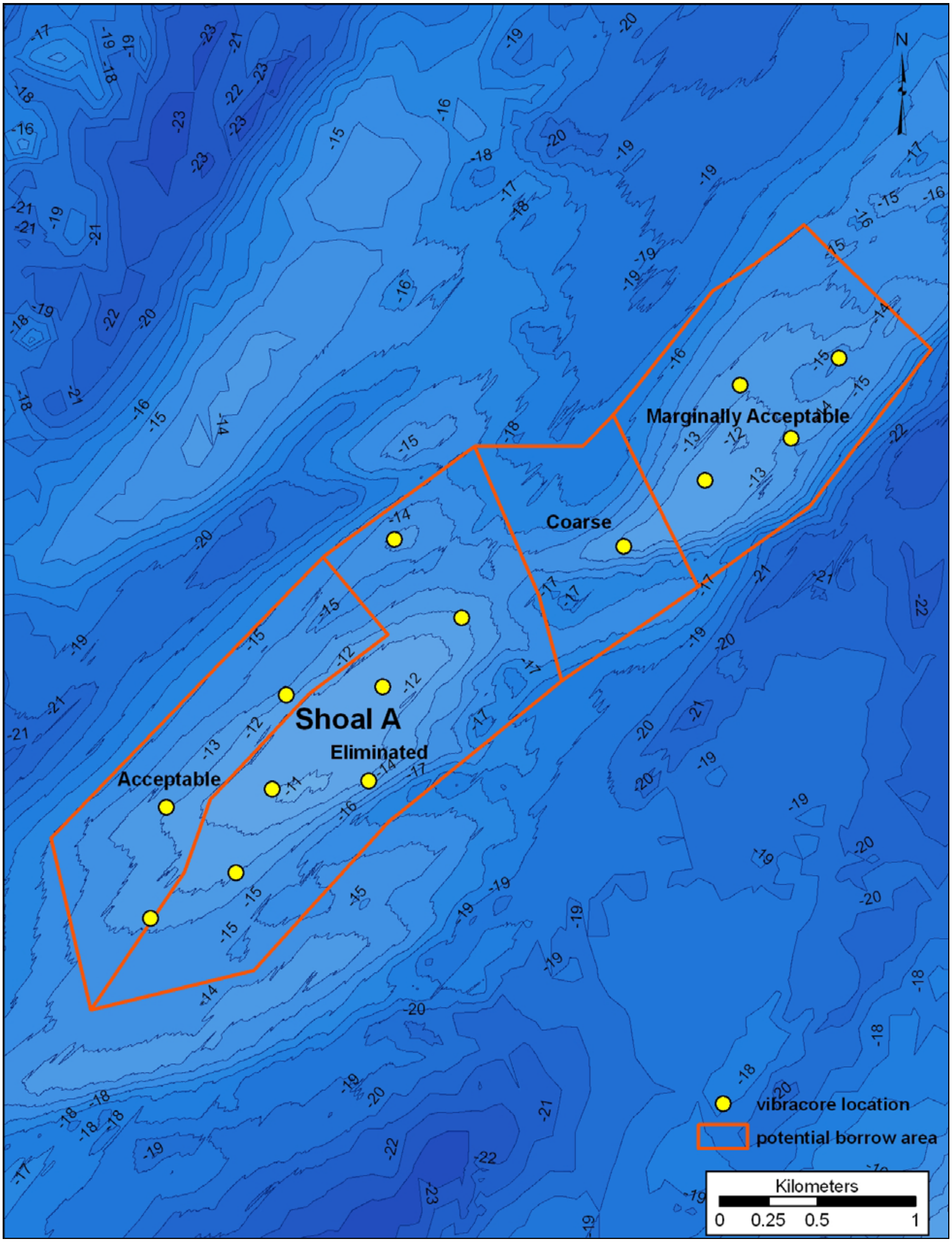


Figure 1.9. Shoal A sand resource acceptability classification by USACE (2008).

2.0 OFFSHORE DREDGING PROCEDURES AT RIDGES AND SHOALS – OFFSHORE DREDGING EQUIPMENT AND TECHNIQUES

(Ancil S. Taylor – C.F. Bean, L.L.C.)

This section describes various types of dredging equipment, methods, procedures, and contractor expectations common to offshore borrow areas used in the restoration of coastal features such as beaches, shorelines, and barrier islands. There are two types of dredges commonly used in the removal of sediment from ridges, shoals, and other types of offshore borrow areas. Hydraulic cutterhead dredges and trailing suction hopper dredges are most commonly used. In some rare circumstances, dustpan dredges have been used, and in even more rare occasions, the Punaise, or as it has been referred to, the "thumbtack," has also been used. This section addresses these types of dredges as well.

2.1 CUTTERHEAD DREDGES

These dredges incorporate the use of a cutterhead near the suction mouth to dislodge the excavated material from the seafloor and assist in the slurrification of the sediment for removal by the suction mouth of the dredge. The dredged material is transported up the suction mouth and propelled away from the dredge via a centrifugal dredge pump. The material is transported through a pipeline to the destination, where it is either shaped into the desired fill dimensions or stockpiled for further rehandling. The following is a description of some of the more significant pieces of equipment and dredging related issues attached to the cutterhead dredge operation.

2.1.1 Dredging Equipment

Cutterheads are designed for different purposes and effectiveness, but in general, most have five to six blades. The cutterhead depicted here has six blades. The shape of the blades is optimized to maximize the "feeding" of material into the suction mouth. The cutterhead is designed to rotate, causing each blade to come in contact with the sediment as it rotates around the axis. Each blade is designed to incorporate certain types of cutting edges. Cutting edges are those leading edges of the blade that come into direct contact with the sediment as the cutterhead rotates on its shaft. This picture depicts a new cutter tooth next to a worn cutter tooth. Cutter edges can be smooth or serrated. The blades may also be outfitted with adapters that allow interchangeability in the types of teeth that can be attached to the blade and adapter. Teeth can be wide to narrow chisel-shaped, or they can be pointed like a pick point. This interchangeability allows the dredge to optimize the production and cost efficiency of the dredge in removal of sediments. Oftentimes, there is substantially more material that actually comes in contact with the blades than is actually removed by the suction mouth. This is referred to as "spillage" and will be addressed later in this section.

Anchors are used to moor the cutterhead dredge and other dredging related equipment to the seafloor for dredging operations. Swing anchors will be used on a cutterhead dredge to swing the dredge back and forth to allow the cutterhead to become engaged with the sediments. Christmas tree anchors may also be used on a cutterhead to stabilize a pivot point near the stern of the dredge around which the dredge can maintain a steady arc as it cuts through the sediments. Pipeline anchors can be used along the length of a floating slurry pipeline, steel or rubber, to moor the pipeline in a location near the dredge while the slurry is transported through it. Ancillary equipment mooring anchors will also be used to temporarily moor other equipment near and around the dredge for easy access by the dredge crew should repairs or typical dredge operations require the equipment.

Anchor placement and techniques commonly involve moving or dragging anchors along the seafloor by anchor handling tug boats with stern winches, anchor handling derricks, and/or anchor booms attached to the dredge. Anchors are designed for various types of material. Optimum anchor design or efficiency focuses on maximizing holding capacity with the least amount of weight. Anchors are designed to penetrate the bottom and bury themselves as soon as possible, minimizing dragging along the bottom before it “holds.” Anchors are commonly attached at the shank with a chain and then a steel anchor wire. Anchor handling boats equipped with a stern winch attach a hook to a pendant wire[1] suspended by a buoy at the surface of the water. The other end of the pendant wire is attached to the tripping ring near the anchor stock. This permits the anchor to be removed from the seabed by backing the flukes out from the bottom. Once removed, the anchor handling boat will either winch the pendant wire aboard, thereby completely removing the anchor from the seabed if the water is deep enough or drag the anchor to the next location if the water is too shallow.

Anchor handling derricks are also attached to the anchor in the same way and will transport the anchor to the next location, similar to the anchor handling boat. The anchor handling derrick affords the anchor shifting operation the additional capability of actually removing the anchor from the water and placing the anchor on the deck of the derrick to assist with unfouling the anchor lines or changing/repairing anchors or wires.

Anchor booms are boom extensions that are attached to the hull of the dredge and used to lift the anchors from the sea bottom and swing the anchor to the next location. The operating principle is simple: at rest, the boom will always move back and away from the cutter, thus preventing the anchor hoisting wire from being dredged up. When the wire is tensioned, the boom will move above the anchor to break it out. When the anchor is broken out of the soil, the wires will automatically pull the boom forward to the new anchor position. After lowering the anchor, the boom will fall back into the resting position. Optionally, the anchor boom can be delivered with a slewing winch, so that the boom can also be moved backwards with a load.

Anchor types include Danforth, Bruce, and Delta in more commonplace applications. There are many variations on these types of anchors, and some companies further modify the anchors with block to “fix” the angle of the flukes to the shank to improve anchor performance.

Wires rope(s) are a consumable for a dredging project. Steel wires come in many different designs, type of lays, number of strands, type of core, etc., depending upon the application. Wire ropes can be found in many locations on the dredging project. They will attach the dredge

---

[1] A pendant wire is a short piece of wire rope that is approximately as long as the water is deep in the vicinity of where the anchor application is. This allows equipment at the surface to attach to the anchor at a location that will remove the anchor from the bottom most efficiently. Oftentimes, a buoy floats at the surface with the pendant wire passing through the buoy, making it easy for the surface equipment (i.e., anchor handling boat) to access the wire.

ladder swing winches to the swing anchors. Wire ropes also will attach Christmas tree winches on the dredge to the Christmas tree anchors. They will attach the floating line anchors to the floating pipeline. They will be used to raft or connect pipelines together for transport. They may be used to tow barges or other vessels on a project. They attach to the dredge ladder to allow the dredge operator to raise and lower the ladder for adjusting the dredge elevation.

Bottom impacts from wires may occur because wire ropes do not float and are subject to sinking to the sea bottom. Wire ropes attached to anchors impact the bottom by dragging along the seafloor. These impacts can be minimized to some degree by deploying additional swing wire floats, sometimes referred to as surge buoys, which attempt to suspend the swing wire above the seafloor. This effort does not eliminate impact with the seafloor but can reduce impact over much of the swing wire length. This application is somewhat less effective in the Christmas tree application due to the rigid and taut application of the anchor wires.

Christmas trees moorings are normally deployed only in offshore environments where the use of spuds is too dangerous due to wave climate. This type of anchoring device is commonly designed to moor the point on the dredge around which the cutter dredge swings. This is most often a point on the stern where the dredge slurry pipeline connects to the hull. Christmas trees are normally a three-point anchoring configuration with a stern anchor and two quarter anchors that stretch forward and angle away from the dredge cut.

Spuds are used to pivot the cutter dredge around an arc to engage the sediments with the cutter. These spuds are of appropriate length to extend into the sea bottom and up to a point above the dredge hull to be held in place by spud keepers, a gantry, or other lifting device and wire ropes. The spud will penetrate into the seafloor to a depth that is a function of the spud’s design, weight, length of time at a given location, the type of material, and resistance to penetration in which the spud is placed. Spuds are used in two general types of configurations for cutter dredges, the fixed spud application and the spud carriage application. The use of spuds in offshore environments is fairly uncommon in the United States, while the use of Christmas tree mooring is fairly uncommon in the international market.

Boats are necessary for effecting operations on a dredging project. Several types of boats are commonly found on projects and require various levels of licensing and training, depending upon the boat class.

Work boats are those boats engaged in the day-to-day operations of facilitating the physical movement of the dredge and its equipment through the project requirements. These boats may assist with anchor handling needs, anchor barge movement, pipeline handling needs, vessel transport, ferrying fuel and/or water to various pieces of floating plant on the project, including the dredge. These boats are commonly measured in horsepower and may range from 200 to 5,000 horsepower depending upon the application. Most cutterhead dredge projects will include a minimum of two of these type boats and sometimes up to four depending upon the type of project.

Crew boats are primarily used to ferry people, small supplies, and groceries to and from various locations on the project to its land-base of operations, the landing. In the offshore environment, one seldom sees crew boats smaller than 14 m in length and up to 37 m in length on some special needs projects. Generally, crew boats travel at speeds of 18 to 23 knots, loads and sea conditions permitting.

Survey boats are used as a platform from which to measure the elevations and locations of the bottom contours. In today's applications, they incorporate differential global positioning systems (DGPS) for determining horizontal location and various types of sonar for measuring water depths at the measured horizontal locations. These boats supply project management with critical information about dredge performance, project layout, and resource planning. They may also provide a platform from which water quality sampling for turbidity and or dissolved oxygen might be measured. In most cases, there is very little need for the boats to come in contact with the seabed except in a situation where anchoring for boat repair or diving operations may be necessary.

Barges are often deployed on projects as platforms for supplies, pipelines, spare cutters, and other major large spare parts. Barges are commonly moored inside a harbor protected from exposure to the wave climate and transported to the project only when it is necessary to utilize that platform offshore. In some cases, these barges are outfitted with spuds for mooring in water depths of less than 12 m or so and in calm water.

2.1.2 Global Positioning System (GPS)

Satellite positioning has become the standard within the industry that would normally be engaged in offshore mining. GPS, with and without differential correction, is the most commonly used form of horizontal positioning in dredging operations today. It utilizes satellite positioning adjusted by a local differential station. Dredges complement the horizontal positioning with various forms of elevation-measuring technology to determine critical elevations around the dredge hull. These elevations are used to extrapolate to a point on the cutter to indicate "dredge depth"[2] and horizontal cutter locations, X, Y, and Z, of the cutterhead. These three coordinates are often reported in state plane coordinates for X and Y and elevation in feet or meters for Z.

GPS positioning technology has grown significantly in the last decade and has become the tool of choice for dredging applications. Limitations are predominantly confined to the occasional but rare loss of a suitable satellite constellation. Accuracy for GPS systems are expected to be submeter. This is more than sufficient for horizontal measurements to accommodate most offshore dredging applications. Reporting is relatively easy once the dredge has been outfitted with the appropriate equipment to measure position via GPS and elevations via the sensors and

---

[2] Dredge depth is a term that is yet to be defined by a standard in the industry. There are at least three different depths that could be reported:
1. The maximum depth of the cutter's impact to the bottom sediments.
2. The depth of the suction mouth that is actually above the maximum depth of the cutter's impact
3. The elevation at which the seafloor remains after dredging.
The difference between Points 1 and 2 could be as much as 0.6 to 1.5 m. The difference between Points 1 and 3 could be as much as 1 to 2.1 m or more.

software to perform the calculations. Reporting the position on a routine basis is simply a matter of programming, and telemetry of the data ashore.

2.1.3 Dredging Techniques in Sand Ridges and Shoals

Deep mining (glory hole) has been a method of mining sand in the offshore environment of the past. The holes are still evident and noticeable off the coast of Florida from coastal restoration/renourishment projects in the 1960's and 1970's. Mining sand in this manner would yield the maximum productivity and cost efficiency for removal. It simply involved placing the suction mouth of the dredge, with or without an agitation device like a cutter, on the seabed and continuing to lower the suction depth until the borrow pit yield diminished. Once the sand quit flowing to the suction mouth, the dredge would either advance or start in a new location.

Thin layer removal is often required when there is only a thin layer of suitable material available for the project. In the context of this document, thin layer could be considered any bank of sand less than 1.8 to 2.4 m thick. There are numerous implications associated with thin layer availability and removal. The thin layer could be overlain and underlain by unsuitable material. Unsuitable material could be defined as a very fine silty mud or a layer of very rocky sediments, neither of which might be considered as suitable for the renourishment project. Due to spillage[3] and mixing around the suction mouth and cutterhead, this unsuitable sediment would be intermixed in large percentages, with the more suitable sediments, diminishing the suitability of the targeted thin layer of material.

Aggressive, maximum spillage is a method of removal that is common when the sediment transportation capability of the dredge is sufficient to permit high percentage concentration by volume of sediment in the slurry. A dredge can move through a bank of material with a high percent of spillage, 40% to 60%, and maintain a high production and lower cost. For example, if the suction mouth or dredging depth is measured 3 to 4 m below the top of the sediment, the dredge will remove only 5 to 6 ft of material, allowing 5 to 6 ft of material to fall behind the cutter and remain on the bottom, resulting in a 50% spillage factor. This method would permit the most efficient removal and dredging cost to the removal effort. Obviously, one of the results of this approach is the homogenizing of the original 3 to 4 m of bank and the resulting removal and spillage of that homogenized mixture. This approach is available only in borrow areas that are of sufficient depth to allow the dredge ladder to continue to swing with a high percent of spillage falling behind the cutter, otherwise, ladder dragging will occur, resulting in adverse production impacts.

Slow, minimum spillage is the other extreme of the aggressive, maximum spillage method described above. This method could result in a spillage factor as low as 15% to 20% and also will result in a much lower productivity with higher cost implications. This method may be chosen by a contractor when available borrow material is limited and a more complete evacuation of the borrow area may be necessary to achieve the necessary quantities. If a dredge has slurry transportation capability limits, the operator could choose to combine these two limitations, resulting in less of an impact due to the reduced spillage. It should be up to the project planner or contractor's project engineer to optimize these production limit relationships and dynamics.

---

[3] Spillage is defined in ERDC/TN EEDP-04-37, June 2007, page 16. This document was prepared by the Engineering Research Development Center for the USACE in Vicksburg, MS.

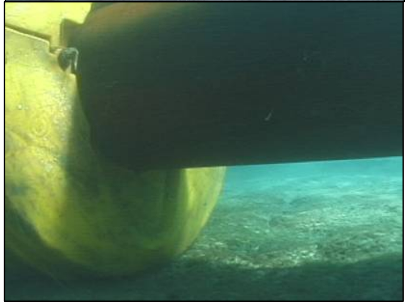
Angle of attack for sea conditions is an important factor in borrow area design. Cutter dredges working in an offshore environment prefer to optimize their angle against the wave climate characteristics. A cutter dredge may swing 80° to 100° through an arc, depending upon the waves. The operator would prefer to keep the seas hitting his hull as close to longitudinal as possible through much of the exposed arc. Operators prefer to avoid any part of the swing where the dredge is exposed to sitting in the trough of the wave.

Borrow area dimensions and locations are very important for the cost and efficiency impacts of the dredging issues related to a project. Both of these issues might determine the type of dredge that would be used by a contractor. This issue is much more involved than could be covered in this document; however, optimizing the dimensions and locations would include almost all of the parameters and issues presented in this document.

2.1.4 Dredged Material Transportation and Pipelines

Floating pipelines (flexibility around the mining area) are very important for a cutter dredge. In most cases, cutter dredges working in the offshore environment will be accompanied by a rough water pipeline made of rubber with floatation wrapped around it. In some cases, the rubber lines are augmented with steel lines to increase length and reduce average cost/unit of length of the rough water pipeline. These steel pipes often have rough water floats wrapped around them as well. This pipeline is connected to the dredge on one end and to another type of pipe on the other end, called riser pipes.

Riser pipelines allow the floating flexible line to be connected to a stationary submerged pipeline. These riser pipes are submerged at an angle to allow some flexibility near the surface while remaining anchored at the seabed by the submerged pipeline or other anchoring device.



Submerged pipelines allow for efficient transportation of slurry over long distances with the lowest exposure to sea conditions. Once placed on the bottom, they are seldom moved by normal wave climates. Tropical storms may cause movement of submerged pipelines if insufficiently anchored.

Submerged reefs can present additional challenges for pipeline transportation of slurries. In some cases, submerged pipelines can be suspended above the bottom with the use of concrete-filled plastic collars wrapped around the pipe as depicted here. In more severe circumstances, submerged pipelines may be prohibited altogether, and floating lines would become necessary. With floating lines, some anchoring devices will be necessary to keep the line in place. These anchors could subject the sea bottom to greater exposure than the concrete-filled plastic collars.

Shore pipelines are used on shore to transport slurry over land. They are normally configured in relatively short pieces of 12 m or so to facilitate transport by truck over the road. As material is deposited at the end of the shore pipeline, the terminus, the sediments are managed to grade. Once sufficient material has been deposited for this 12-m section of fill, another pipe is added and connected to the end of the line. These connections are made by flanges or telescopes. This picture depicts a flanged connection on a 32-in. diameter pipeline.

Installation and removal of pipelines are an important piece of the mobilization and demobilization effort. The three major categories of pipelines (floating, submerged, and shore) may commonly be installed and ready before the dredge arrives on site. Submerged lines are placed on the sea bottom in favorable sea conditions. The floating lines are connected via riser pipes to the submerged line and anchored in position awaiting the arrival of the dredge. These operations require people, boats, barges, and cranes to make these pipelines ready for delivery of sediment. The shore pipelines are placed at a convenient location on shore and made ready and available for adding at the end of the pipeline when the fill crew is ready for them. The shorelines can be delivered to the shore locations by truck, by barge, or both. The submerged pipelines are commonly towed to the site in lengths of 244 to 305 m in rafts[4].

The floating lines can be towed into position, or oftentimes they are broken down in smaller segments, stored, and transported on a barge. Upon arrival on a job site, they can be reassembled.

Depths of water required for pipeline installation will vary with the project specifics. Conventional equipment will likely need a water depth of 1.8 to 2.4 m to accommodate the barge and/or tender boat that is used to work with the pipelines. Water depths that exceed 12 to 15 m will require extra measures to protect the submerged line during placement and removal.

Booster applications are becoming more common as borrow areas get farther from the placement sites. Boosters are placed in the pipeline at a point between the dredge and the pipe terminus. If the booster must be placed offshore, it may commonly be placed at the downstream end of the floating pipe, just ahead of the riser pipe. In the case where a booster is placed behind a section of submerged pipeline, a riser will leave the bottom, attach to the intake side of the booster, and then from the discharge of the booster back through a riser pipe to another section of submerged line or to another line. In some cases, there may be multiple boosters placed in the line to provide the necessary transport energy for the sediment slurry.

---

[4] A raft is a series of pipes, usually six to eight, tied together at several locations along their length for long distance transport over a water body.

2.1.5 Turbidity Sources During Dredging

Turbidity sources during dredging are to be expected. The primary sources of turbidity will be around the cutterhead and the suction mouth. Other areas will be in the vicinity of the swing wires as they drag along the sea bottom and anchors as they are placed, set, or moved. Another area is sediment that may be washed from the decks during cleaning or rain events. Turbidity around the cutterhead occurs as the agitation and scouring of the sediments around the cutter take place. As mentioned earlier, spillage is the material that is actually impacted by the cutter or suction but does not enter the flow regime in the pipeline. It falls back to the seafloor either immediately with coarse material or migrates away from the area with high currents and/or very fine sediment. Another significant source of turbidity is the action of the reverse flow carrying sediment from the pipeline when the pumping ceases. On many occasions throughout the day, the dredge must cease pumping for operational or repair issues. When this occurs, there is a natural emptying or back flushing of the pipeline through the suction mouth in which it entered. This creates a plume around the suction mouth.

Ancillary operations usually involve boats and barges. Propeller wash in the vicinity of the sea bottom is the most common cause of turbidity around the ancillary operations.

Placement areas are another significant source of turbidity. Effluent run-off from the discharge operation carries fine particles back to the receiving water body. These fine particles will be carried downstream for a distance that is a function of the grain size and current velocity.

Types of containment include passive approaches such as extending the length of training dikes along the shore to provide longer settling distances. Often these are difficult to maintain due to sea conditions, tidal fluctuations, and erosion of the base of the levee due to the slurry itself. Other, more aggressive approaches have involved building cells along the shoreline with a weir to enhance settling within the cell. These cells are more difficult to prepare and require a larger, more extensive shore base of equipment. In many cases, these cells trap very fine material that may be considered less suitable shore renourishment material.

2.2 HOPPER DREDGES

Hopper dredges are commonly used in offshore conditions where exposure to sea conditions can adversely impact productivity and efficiency of other types of dredges. They are often configured like a ship with a cargo hold designed for dredged material. They are equipped with one to three *dragarms*, which are pipe structures suspended down the side of the hull to the seafloor. On one vessel, the USACE's *Wheeler*, there is a dragarm that extends through the keel of the vessel to the seafloor. Dredged material is removed from the bottom through these dragarms and placed in the cargo hold of the vessel for transport. The vessel transports the material to a remote location for discharge through the bottom of the hull or for discharge from the hull through a pipeline. Once the vessel is emptied, it returns to the dredging location to repeat the loading process, thereby completing a dredge cycle. A dredge cycle includes the loading phase, which may incorporate multiple turns, the sail to the discharge location, the discharge phase, either pump-out or bottom dump, and then sailing back to the dredging location.

2.2.1 Dredging Equipment

There are many aspects of a hopper dredge that are critical to the operations and effectiveness of the vessel as a dredge. The dredge is equipped with *dragheads*, which are attached to the end of the dragarm. These dragheads are designed for many different applications and types of material. Since this paper focuses on sand ridges and shoals, we will limit the discussion to sand and granular types of material.

The excavation of sand from the seafloor with the application of a draghead is primarily a combination of cutting the sand with *knives* or *teeth* and/or *waterjets* and/or scouring the sand with the passing of water over the sand into the draghead. Most dragheads are made up of several major components. These are the helmet, the visor, the teeth, water-jets, the trunnion pin, and water-flap. On some projects, dragheads are fitted with “bomb bars” to exclude large unexploded ordnance (UXO), or munitions and explosives of concern (MEC). In recent years, the addition of a turtle deflector has been added to reduce the mortality rate of turtles in the dredge area.

Some types of dragheads are designed for 100% scouring, while others are designed primarily for cutting with a smaller benefit from scouring. The application of teeth in a draghead is augmented with the use of a *water-flap*, which acts as a lever arm behind the draghead to force the teeth into the sand. As water flows under the water-flap at increasing velocity, the Venturi effect[5] pulls the visor of the draghead down, thereby leveraging or forcing the knives or teeth into the seafloor. Water-jets are also used to more efficiently remove sand from the seafloor. The jets are high velocity streams of water directed vertically downward into the sediment to inject water into the pores between the sand particles. This injection separates the sand particles and places them into suspension to be removed by the draghead as it passes over. The pressure of the jet water entering the draghead may range from 70 to 200 psi, depending upon the application. Once the sediment enters the draghead, it flows up the dragarm to the centrifugal dredge pump, where it is propelled into the hopper. This process continues until the load in the hopper dredge reaches a maximum legal or practical draft of the vessel. This load is optimized by allowing water to leave the cargo area via valves and water ports located in and around the hopper void, and leaving the sand in the hopper. In most cases, fines are carried along with the overflowing water back into the sea, either over the side of the vessel or through the bottom of the hull. On most projects in the United States today, water leaving the vessel passes through a matrix of screens to capture evidence of a “biological take.” The screens are periodically inspected by certified biologists in accordance with permit requirements placed on some projects.

---

[5] The Venturi effect is the fluid pressure that results when an incompressible fluid flows through a constricted section of pipe. The Venturi effect may be derived from a combination of Bernoulli's principle and the equation of continuity. The fluid velocity must increase through the constriction to satisfy the equation of continuity, while its pressure must decrease due to conservation of energy: the gain in kinetic energy is supplied by a drop in pressure or a pressure gradient force. The limiting case of the Venturi effect is choked flow, in which a constriction in a pipe or channel limits the total flow rate through the channel, because the local pressure in the constriction cannot drop below the vapor pressure in a liquid or exceed the speed of sound in a gas. Using Bernoulli's equation in the special case of incompressible fluids (such as the approximation of a water jet), the theoretical pressure drop ($p_1 - p_2$) at the constriction would be given by $\frac{\rho}{2}(v_2^2 - v_1^2)$. The Venturi effect is named after Giovanni Battista Venturi, 1746–1822, an Italian physicist.

2.2.2 Hopper Dredge Loading

Hopper dredges maneuver through a borrow area removing 9 to 46 cm of material over the width of a draghead that may vary from 1.5 to 4 m in width. They may trail[6] at speeds of 1 to 3 knots, depending upon the application. Positioning of the vessel is universally provided via GPS described above. Accuracy in the horizontal plane at the surface is commonly submeter. Accuracy on the seafloor depends upon the level of monitoring available on the vessel. Dragarms and dragheads do not naturally hang vertically as they ride along the seafloor. They move back and forth with the influence of the seabed. If a vessel is not equipped with angle-measuring equipment on the dragarm sections, the actual locations of the dragheads will be extrapolated based only upon the location of the hull.

In the United States today, hopper dredges are required to maintain the “Silent Inspector” to work on USACE projects or permit projects. This monitoring equipment automatically records and reports the following information to the USACE:

- Dredging position;
- Dredging depth;
- Vessel displacement;
- Cargo tonnage;
- Tons of dry solids;
- Vessel speed;
- Vessel heading;
- Dredge cycle time;
- Slurry flow-rate;
- Slurry density; and
- Vessel status (loading, sailing, dumping, and idle).

As the hopper dredge trails through the borrow area, it is steering toward the available bank of material. Narrow, restricted, and small borrow areas require significant maneuvering that adversely impacts the productivity of the dredge. Turning of the dredge in small diameter circles requires temporary suspension (4 to 9 minutes) of dredging, thereby increasing cost. An ideal borrow area is one of sufficient length to match the required loading time divided by the optimum trailing speed divided by 2 times 1.25. For example, if a ship requires approximately 60 minutes to achieve its full load and it trails at approximately 2 knots, according to this formula, a borrow area length of 2,316 m would be an optimum dimension. Borrow areas that incorporate the production needs of the hopper dredges will result in more efficient pricing to the customer.

In some cases, the hopper dredge may be required to crab along the trail length. This would be similar to an airplane coming in for a landing on the runway when you see the longitudinal alignment of the plane in misalignment of the runway due to these side forces. Hopper dredges are affected by winds and current, resulting in side forces that must be overcome by the propulsion systems aboard the vessel. These impacts reduce the efficiency of the dragheads, and in some cases, require the elimination of the use of one or the other dragheads due to the side forces on the vessel.

Sand ridges and shoals are often found in the vicinity of protected hard bottom resources. These protected areas should be programmed into the positioning system of the hopper dredge

---

[6] Trailing is the term used to define the action of the hopper dredge as it is removing material in the borrow area.

so they are readily available and visible by the ship's master, mates, and operators. The areas can be easily avoided in most circumstances with the application of this technology. As for overflow impacts, hopper dredges incorporating the load optimizing procedures will always allow water and fines to overflow from the hopper during the loading phase. The amount of fines overflowing with the water is primarily a function of the grain size of the material and the relationship of the infill rate to the settling surface area in the hopper. The smaller the settling area, the larger the percentage of the fines that will escape overboard. The greater the flow-rate into the hopper with any given settling area, the greater the percentage of fines that will escape overboard. To retain fines or to "top off" the load, some operators will reduce the inflow from one or all dragarms to reduce the ratio of inflow to the settling area.

2.2.3 Pump Ashore Operations

If a hopper dredge is working a sand ridge or a shoal, it is likely involved in a mining effort of some sort to beneficially use the material in a shoreline restoration project or reclamation area. If so, the dredge will likely be rehandling the material from its cargo hold to its ultimate location onshore through a pipeline. This is considered a direct pump-out effort and involves a more extensive use of additional equipment. A direct pump-out operation may incorporate some or all of the following equipment:

- Anchorage by anchors or other suitable equipment;
- Floating pipeline (hose) extending from the bow of the ship;
- Booster(s) to assist with the discharge of the material to the shoreline;
- Riser pipeline (described earlier);
- Submerged pipeline (described earlier);
- Shore pipeline, dozers, tractors, lights, and maintenance equipment located on shore;
- Tug to assist the connection of the dredge to the pipeline;
- Mono-buoy to assist with the connection of the pipeline;
- Crane barge for working with floating equipment in the vicinity of the project;
- Crew boat(s) for moving people and equipment around the site; and
- Survey boat(s) to monitor progress and productivity of the dredge.

Anchorage areas, not withstanding the specific project requirements, will commonly be located at a point closest to the required fill area at the contour that incorporates the draft of the loaded vessel plus the tide variation and the expected sea conditions. For example, if a hopper dredge is drafting 6.7 m of water when it is loaded, the pump-out location may be located in approximately 8.2 to 8.5 m of water.

The operators will always look at the slope of the contouring seabed. In some cases, very long shallow slopes may indicate 1,000:1, where each additional foot of depth may significantly increase pipeline lengths. Those anchorage location decisions include optimizing the relationships between load and draft depths and varying discharge distances.

Once the pump-out location is established, an anchoring system must be installed. Often a mono-buoy is utilized to anchor the end of the hose and make it available for the hopper dredge upon arrival at each pump-out event, often several times a day. This mono-buoy can be secured to the bottom with a three-point anchor system that may extend out from the mono-buoy several hundred feet. In other cases, the hose can have a small anchor attached to the end that is retrieved by the assist boat when the hopper dredge comes into position. The control of the pump-out hose is transferred to the bow of the hopper dredge, where the connection is made. At the completion of the pump-out sequence, control of the hose is transferred back to the assist boat or simply dropped to the seafloor. The other end of the hose is normally connected to either a riser pipe leading to a submerged steel pipeline laying on the seafloor, or it connects to a booster application if one is incorporated into the system.

Once the connection is made between the hopper dredge and the hose, the pump-out process begins. The dredge operator initially pumps water through the pipeline until water is received at the terminus of the discharge line. This forces any air that may be in the line out through an air valve located just upstream of the submerged pipeline. This keeps air out of the subline so it does not inadvertently rise to the surface or lift from the seafloor. Once the discharge line is stabilized with water, the operator begins to allow sand into the system from the cargo hold of the dredge. Jet water inside the hopper facilitates the mixing of the sand with water and its entry into the slurry pipeline. This process will continue with the operator throttling the sand into the system to the limit of the system's horsepower to handle the velocity and density. Once the hopper hold is sufficiently evacuated, the operator will likely flush the floating hose with water for a few minutes, and possibly the submerged line depending upon the type of material, the project conditions or the plans for future use of the line in this particular location. Once the flushing action is completed, the dredge disconnects from the hose and returns to the dredging area for another load. This cycle repeats itself until the fill at this location has been completed.

Turbidity around the hopper dredge operations occurs in a few locations. The most significant contribution to turbidity occurs as a result of the load-optimizing process. Overflowing of the hopper is intended to maximize the load of sand in the hopper. This process will carry fines overboard that will be entrained in the water column at some level. Some hopper dredges overflow below the surface of the water, some overflow at the surface, and some overflow at both locations. Another area of turbidity exists around the dragheads as they move through the sediment. Not all sediment impacted by the draghead is removed by the suction capacity. Incorporating turtle-excluding devices (TEDs) increases the interaction of the draghead on the seafloor with the sediments, thereby increasing turbidity around the dragheads. Another area of turbidity exists when the propulsion of the hopper dredge impacts the seafloor, stirring up fines laying on the sea bottom. The final significant area of turbidity exists around the fill area as the water is returning to the sea from the fill operations.

2.3 OTHER OFFSHORE DREDGING EQUIPMENT AND TECHNIQUES

2.3.1 Dustpan Dredges

The dustpan dredge is ideal for the excavation of granular sediment. The first use of the dustpan technology in the offshore mining environment was the dredge *Beachbuilder*[7], designed, built, and operated by The Bean Companies in New Orleans, Louisiana. This

---

[7] The *Beachbuilder* was redesigned and modified as a cutterhead dredge, renamed the *Ohio,* and mobilized to the Middle East in 2008 by Great Lakes Dredge and Dock Company.

photograph of the dustpan dredge, *Wallace McGeorge*, was also designed, built, and operated by The Bean Companies until it was sold to and renamed by the Pine Bluff Sand and Gravel Company in 1991.

Dustpan technology relies upon agitation of the bottom sediments through the use of water jets near the suction head to excavate and remove sand from the seabed. This technology works well in sediments that are relatively clean, free from silt, mud, and shell or shell fragments.

The dustpan-operating principle is based upon winching itself forward into a bank of sand. The two large privately owned dustpans have a suction head that is rectangular shaped approximately 9 to 10 m wide and approximately 46 to 60 cm high. A row of jets injecting high velocity water streams into the sediment are along the top of the dustpan head, and in some cases, along the bottom of the head. The dredge pulls itself forward, allowing the jets to collapse, slurrify, and remove the sediments that fall in front of the suction mouth. Bank heights of 1.2 to 2.4 m may be removed in each pass, requiring multiple passes in higher banks of material.

The *Beachbuilder*, the larger American dustpan dredge, was equipped with six anchors, three forward and three aft, for positioning itself offshore. The *Wallace McGeorge*, the smaller dustpan dredge, utilizes two forward anchors and stern propulsion for positioning on the Mississippi River, its sole operating environment.

Except for the operating procedures and the longer floating hose that would be required to accommodate the larger working area of the dustpan, most other ancillary operations in the offshore environment are similar to the cutterhead dredge operations described above.

2.3.2 Punaise

The Punaise or “thumbtack,” as it was commonly referred to, is a Dutch-designed system from the 1980’s intended to mine sand in either the offshore or inland environments. The technology has been slow to catch momentum primarily due to the requirement of significant banks of sand to make it a productive device. It works on a similar principle to that described in **Section 2.1.3**. The Punaise is composed of a watertight housing containing the dredge pump, motor, and ballast tanks. It is connected to the shore station via an umbilical that consists of control connections, power supply, and a slurry discharge line. While in operation, the Punaise rests on the bottom of the seabed and pumps sediment without impact to surface vessels. Once positioned at the appropriate location for sinking to the bottom, the ballast tanks are filled, and the Punaise settles to the bottom. Water jet nozzles are then activated, which allow the vertical support to settle into the sand bottom so the dredging process can begin. As material is removed, a pit is formed with the Punaise located at the lowest point. The submerged machine excavates by means of hydraulic erosion and agitation. The Punaise transports the sand ashore via a small diameter pipeline, usually less than 20 in. Anchors, wires, and boats are still a necessity for this application.

3.0 PHYSICAL IMPACT PRODUCING FACTORS ASSOCIATED WITH SAND MINING ON SHOALS OFFSHORE MARYLAND

(Mark R. Byrnes – Applied Coastal Research and Engineering, Inc.)

As described in **Section 2.0**, sand dredging on the continental shelf almost exclusively employs hydraulically-operated equipment for excavating and transporting sand resources from the Federal OCS to nourish onshore beaches (Herbich, 1992). In general, the distance from the borrow site to the beach determines the dredging and sand transport method to be used (Louis Berger Group, 1999). The most commonly used methods are a hydraulic cutter-suction dredge, which pumps fluidized sand through a pipeline to the beach, and a hopper dredge, with two dragheads and a hopper. When the hopper is filled, the dredge lifts the dragheads and transports the sand to shore for unloading.

Each dredging method generally is employed based on project site distance from the borrow source. Cutter-suction (versus cutterhead) dredges and pipelines are used primarily for transport distances of less than about 5 to 6 km, although the distance can be larger depending on sea conditions. These dredges are used most prominently throughout the industry, having a rotating cutter surrounding the intake end of the suction pipe (**Section 2.0**). The method of sand extraction and transport is quite efficient, resulting in about 90% to 95% of excavated sand reaching the beach. Limiting environmental factors for the cutter-suction dredge for economic operations include a maximum water depth to dredge of about 30 m, a maximum cut width of about 175 m, a maximum ocean wave height of 2 m, a maximum swell wave height of 1 m, and maximum cross currents of about 2 knots (Louis Berger Group, 1999).

Hopper dredges are the preferred methodology when borrow sources are greater than 6 km from the beach. These dredges are self-propelled and suitable for open ocean sand mining and loading a self-contained hopper while the ship is underway. Loading occurs as the ship moves ahead at a speed of about 2 to 3 knots. Unloading can be completed via bottom discharge, pump discharge, or mechanical removal. Some main advantages of this dredging method are 1) it is a self-propelled, independent operation; 2) loads can be transported over long distances; 3) production rate is high; and 4) operations can take place in relatively deep water and higher sea-state conditions. For economical operations, maximum practical water depth is about 46 m. Maximum wave heights can be about 4.6 m, and cross-currents of about 3 knots are tolerable. Peak sailing speed is about 17 knots, and minimum operating water depth is about 4.6 m.

The purpose of this section is to provide a qualitative evaluation of operational factors potentially influencing shoal morphology and biological communities on the Federal OCS offshore Maryland (addresses components of the second and fourth questions in **Section 1.2**). Primary areas of concern include specific locations for sediment removal and the quantity of sand being removed, the likelihood of sediment suspension/dispersion associated with sand excavation from shoals, the magnitude and extent of sand deposition resulting from suspension/dispersion during dredging, and any other seafloor disturbances that may occur as a result of dredging.

3.1 EXCAVATION QUANTITY AND SEDIMENT REMOVAL

USACE (2008) presents a comprehensive evaluation of potential environment factors influencing shoal habitat and fauna. Sediment removal from portions of selected shoals was evaluated based on required sand quantities for beach nourishment through 2044 and sedimentologic characteristics of shoal deposits. Based on beach nourishment project performance since 1998 for the Ocean City, Md., beaches, USACE (2008) determined that approximately 5.2 to 11.5 million cubic meters (x 10^6 m^3) (6.8 to 15 million cubic yards [Mcy]) of sand would be required to maintain beach stability through 2044. The challenge was to identify offshore sand deposits that could supply this quantity of material in a manner sensitive to fisheries and the environment.

The availability of beach-quality sand from the continental shelf throughout the study area has been evaluated by the MGS, MMS, USACE, and other investigators (Field, 1980; Louis Berger Group, 1999; Conkwright et al., 2000; MMS, 2003; USACE, 2008). Although sand deposits occur in a variety of features on the shelf, shore-detached shoals were found to contain large quantities of sand suitable for beach nourishment. Furthermore, USACE studies of the ebb-tidal shoal at Ocean City Inlet identified sand suitable for beach nourishment; however, deposits typically were more heterogeneous than those associated with offshore shoals. Conversely, MGS found that shore-attached ridges typically contain fine sand and mud, which generally is considered unsuitable as beach fill. MGS also evaluated sand characteristics associated with flat seafloor areas (sheet sands) and found variable sand thickness, often only several feet, generally overlaying fine-grained deposits unsuitable as beach fill. Such depositional characteristics make sheet sands difficult to dredge. Lastly, subsurface paleochannel fill deposits are limited in size and extent, and they are generally buried under relatively thick fine-grained deposits. Again, these kind of sand borrow sites are time consuming to dredge and often result in significant environmental impacts.

3.1.1 Sediment Availability

USACE (2008) performed a detailed analysis of potential candidate shoals offshore Ocean City from which sand might be available for beach nourishment. Nine shoals were identified from which approximately 316 x 10^6 cu m (413 Mcy) was designated as beach quality sand (see Table 4-1 in USACE [2008]). This sand volume is far greater than beach nourishment needs at Ocean City for the foreseeable future. As such, each identified shoal was evaluated by USACE to determine whether any engineering, economic, or environmental factors might favor a specific borrow site. Based on this analysis, Weaver Shoal, Isle of Wight Shoal, and Shoal A were identified as having high-potential for providing beach-quality sand (see **Figure 1.6**).

Weaver and Isle of Wight shoals are located approximately 13 km from the center of Ocean City beaches. Offshore sand resource evaluations completed by MGS personnel determined that approximately 63 and 54 x 10^6 cu m (82 and 71 Mcy) of beach quality sand, respectively, were available from each shoal (USACE, 2008). Shoal A is located farthest offshore (about 15 km from Ocean City) and contains the least amount of beach quality sand (about 28 x 10^6 cu m [37 Mcy]). These data were further analyzed in USACE (2008) to better describe the location and quantities of beach quality sand deposits for each of these shoals (designated “acceptable” on **Figures 1.7**, **1.8**, and **1.9**). Approximately the southern half of Weaver Shoal was determined to be acceptable as beach fill, the volume of which was estimated at 20.1 x 10^6 cu m (26.3 Mcy) relative to the 18-m depth contour (National Geodetic Vertical Datum [NGVD], USACE, 2008) (**Figure 1.7**). For Isle of Wight Shoal, the north-central portion of the shoal complex (“Acceptable” and “Marginal” areas **Figure 1.7**) was determined to contain approximately 23.5 x 10^6 cu m (30.7 Mcy) of beach fill relative to the 17-m (NGVD) depth contour. At Shoal A (**Figure 1.9**), only the northwestern portion of the shoal complex was classified as acceptable for beach fill, but northeastern portions of the shoal were marginally acceptable, resulting in about 8.1 x 10^6 cu m (10.6 Mcy) of sand relative to the 17-m (NGVD) depth contour. Based on their analysis, USACE (2008) determined that approximately 51.7 x 10^6 cu m (67.6 Mcy) of beach quality sand is available to nourish Ocean City beaches. This volume is about 4.5 times the amount required through 2044. Geological characteristics for each area are provided in USACE (2008). This information was used to complete numerical modeling of seafloor elevation changes as documented in **Section 5.0**.

3.1.2 Sediment Removal

Concerns regarding sand removal effects on physical processes and biological habitat prompted USACE (2008) to recommend restrictions regarding sand dredging along shoal crests shallower than 30 feet. Based on shoal characteristics listed in USACE (2008), four potential dredging scenarios were developed for evaluating changes in physical processes on shoals containing acceptable sand deposits for beach nourishment along Ocean City beaches. Specific sediment removal scenarios for this study include

- dredging a hole over a designated area on the shoal;
- dredging the leading edge of a shoal;
- dredging the trailing edge of a shoal; and
- dredging in a striped pattern to facilitate recruitment of benthic invertebrates into dredged areas.

Removal of sediments from borrow sites can alter seabed topography, creating pits that may refill rapidly or cause detrimental impacts for extended periods of time. The term borrow site can be misleading because often material is returned only by natural sediment transport processes. Many years have been required for some offshore borrow sites to refill to pre-dredging profiles (Wright, 1977), whereas other borrow sites have been known to remain well-defined years after dredging (Marsh and Turbeville, 1981; Turbeville and Marsh, 1982; USACE, 2008 [Annex B3]). Intentionally locating borrow sites in areas of rapid deposition may dramatically reduce the time for refilling (Byrnes and Groat, 1992; Van Dolah et al., 1998). In general, shallow dredging over large areas causes less harm than dredging small but deep pits, particularly pits opening into a different substrate surface (Thompson, 1973). Deep pits also can hamper commercial trawling activities and harm level-bottom communities (Thompson, 1973). If borrow pits are deep, current velocity is reduced at the bottom, which can lead to deposition of fine particulate matter, and in turn, a biological assemblage much different in composition than the original. Recovery of the physical environment and benthic assemblages to pre-dredging conditions will probably take decades for a deep pit dredged 3.6 km offshore Coney Island (Barry A. Vittor & Associates, Inc., 1999).

Seabed topography and benthic communities can be altered when sediment is removed by dredging bathymetric peaks such as ridges or shoals rather than level sea bottoms or depressions. Numerous benthic organisms and fishes inhabit offshore shoal areas, but specifics regarding species, assemblages, and ecological interrelationships between the topographic features and associated biota are not well known. Potential long-term physical and biological impacts could occur if dredging significantly changes the physiography of shoals. However, Burlas et al. (2001) monitored borrow sites with bathymetric high points off northern New Jersey and found that essentially all infaunal assemblage patterns recovered within 1 year after dredging disturbance, except recovery of average sand dollar weight and biomass composition, which required 2.5 years.

For the dredging scenarios listed above, perhaps the most desirable location for dredging is associated with areas of net long-term deposition. Extracting sand from a depocenter implies that recovery or infilling processes would proceed in a way consistent with natural long-term depositional processes for the borrow area (Byrnes and Groat, 1992; Van Dolah et al., 1998). Typically, this refers to the leading or downdrift margin of a shoal. Determining the magnitude and extent to which long-term seafloor changes occur on and adjacent to shoals requires one to accurately evaluate sequential bathymetric surveys. For Weaver Shoal, Isle of Wight Shoal, and Shoal A, bathymetric data collected by NOAA between 1975 and 1978 were compared with USACE bathymetric data collected in 2002 to document net change.

Figure 3.1 records net changes in seafloor elevation relative to shoal morphology. Blue colors represent deposition, and yellow to red colors represent erosion. Colored polygons illustrate the locations of potential dredging sites where scenarios listed in **Table 3.1** were simulated (see **Section 5.0**). Approximately 1.1 to 1.7 x 10^6 cu m (1.4 to 2.2 Mcy) were extracted from each shoal. This quantity range was based on the history of beach fill needs for Ocean City and Assateague Island as extracted from similar shoals offshore Maryland (USACE, 2008). One primary observation is that the leading edge of Weaver Shoal can be identified clearly as an extensive depositional area along the southern margin of the shoal. Byrnes and Groat (1992) identified a portion of Ship Shoal (Louisiana) with similar depositional characteristics as an ideal location for a sand borrow site because dredging would occur in an area of active natural deposition, potentially minimizing long-term environmental damage.

Table 3.1. Potential dredging scenario characteristics.

Shoal Name	Sub-Area	Removal Type	Excavation Depth (m)	Removal Volume ($x10^6$ cu m)
Weaver	Crest	Hole	3	1.3
	Crest	Striped	4	1.7
	Leading edge	Slice	2	1.4
Isle of Wight	Crest	Hole	2	1.5
	Crest	Striped	4	1.4
	Trailing edge	Slice	2	1.7
Shoal A	Trailing edge	Hole	2	1.4
	Trailing edge	Striped	3	1.1

*Striped scenarios include five dredging strips 50-m wide and 50-m apart.

Bathymetric change data also suggest that the eroding portion of a shoal's trailing edge may be an area to avoid. Because this part of the shoal often is net erosional, the area provides a source of sediment to depositional regions of the shoal (**Figure 3.1**). As such, dredging in these areas may have a direct impact on natural erosion processes that source downdrift depocenters, thereby disrupting natural shoal evolution. As a result, polygon locations for simulated dredging illustrated on **Figure 3.1** were sited within acceptable sand resource areas to avoid active erosion zones. Shoal A was the only sand borrow area where this could not be completely avoided.

Borrow site geometry was also considered when assessing physical impact producing factors for each shoal. The intent was to design dredging scenarios that are reasonable in terms of dredging requirements (e.g., dredging distance and depth) and avoid concerns regarding the physical and biological environmental impacts of the dredging process. For instance, when dredging a hole on the shoal, it was important to avoid deep sand borrow pits because negative environmental impacts are known to be associated with this type of dredging (Thompson, 1973; Byrnes et al., 2000; Byrnes et al., 2003; Kelley et al., 2004; Hammer et al., 2005). As such, dredging depths for various simulations never exceeded 4 m, and the area over which dredging simulations occurred was large. Furthermore, dredging in a striped pattern overreach of the shoals was simulated because studies suggest that this procedure may facilitate recruitment of

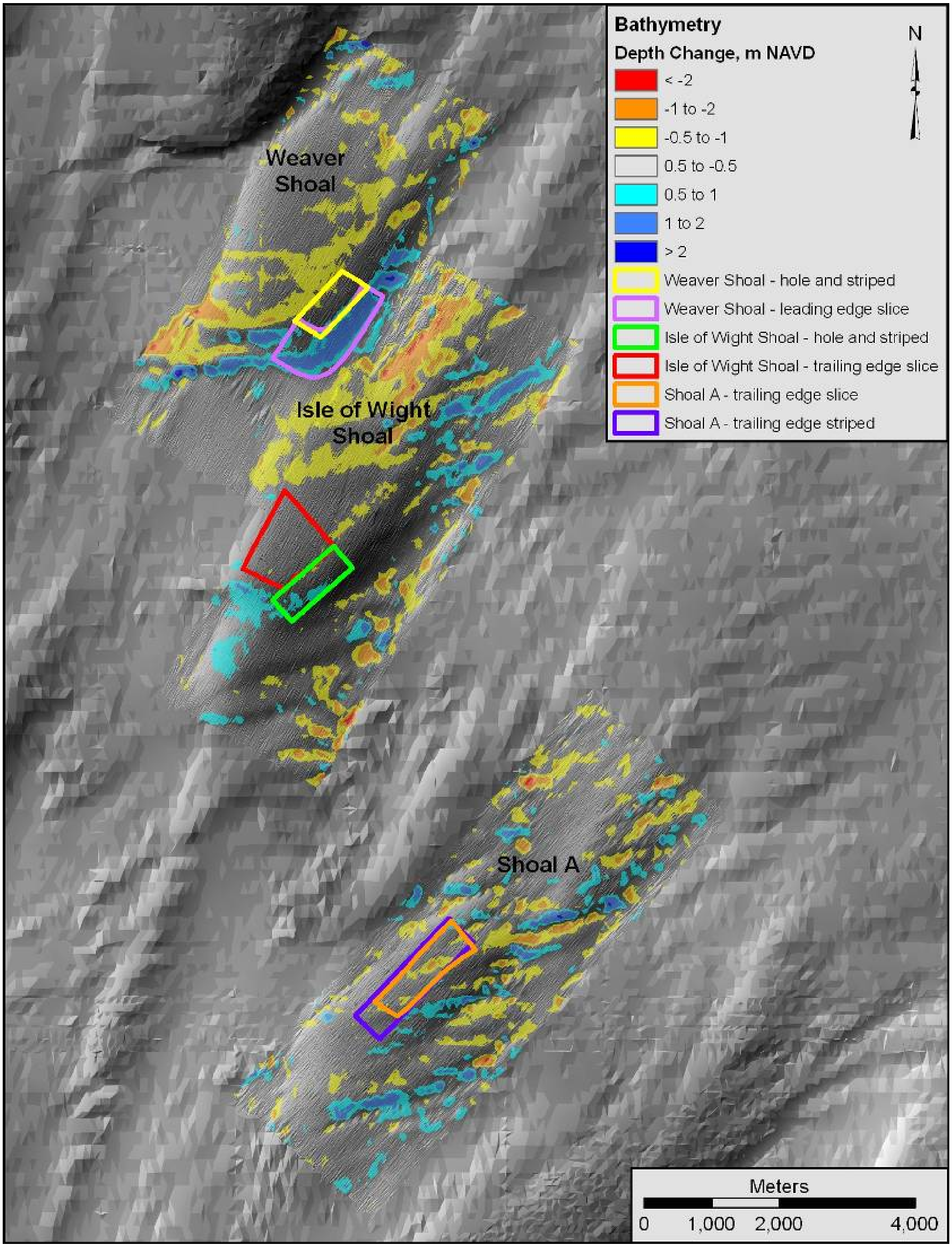


Figure 3.1. Areal extents for selected dredging scenarios for each shoal relative to seafloor changes recorded between 1975/1978 and 2002.

benthic invertebrates into the dredged borrow site (USACE, 2008). Increased surface area associated with this dredging technique also is expected to promote transport and redistribution of sediment after initial sand excavation, leading to a more uniformly distributed infilling process.

3.2 SEDIMENT SUSPENSION/DISPERSION (TURBIDITY)

Dredging causes suspension of sediments, which increases turbidity over the bottom. Turbidity undergoes dispersion in a plume that drifts with water currents as suspended sediments from dredging settle. The extent of suspension/dispersion depends on a multitude of factors, including the type of dredging equipment techniques for operating the equipment, amount of dredging, thickness of the dredged layer, sediment composition, and sediment transport processes. Although turbidity plumes associated with dredging often are short-lived and affect relatively small areas (Cronin et al., 1970; Nichols et al., 1990), resuspension and redispersion of dredged sediments by subsequent currents and waves can propagate dredge-related turbidity for extended periods after dredging ends (Onuf, 1994). Biological responses to turbidity depend on all of these physical factors, coupled with the type of organism, geographic locations, and the time of year. In the case of sand dredging from offshore shoals for beach nourishment, turbidity plumes at the borrow site are virtually nonexistent due to rapid settling of sand-sized particles, resulting in minimal if any sedimentation impacts relative to background transport processes (Louis Berger Group, 1999).

Herbich and Brahme (1991) and Herbich (1992) reviewed sediment suspension caused by existing dredging equipment, and discussed potential technologies and techniques to reduce suspension and associated environmental impacts. In general, cutterhead suction dredges produce less turbidity than hopper dredges. A cutterhead suction dredge consists of a rotating cutterhead, positioned at the end of a ladder, which excavates the bottom sediment. The cutterhead is swung in a wide arc from side-to-side as the dredge is stepped forward on pivoting spuds, and excavated material is lifted by a suction pipe and transferred by pipeline as slurry (Hrabovsky, 1990; LaSalle et al., 1991). Sediment suspension is caused by rotating action of the cutterhead and swinging action of the ladder (Herbich, 1992). Well-designed and properly operated cutterhead dredges can limit sediment suspension to the lower portion of the water column (Herbich and Brahme, 1991; Herbich, 1992). Turbidity can be reduced by selecting an appropriate cutterhead for a given sediment, determining the best relationship between cutterhead rotational speed and hydraulic suction magnitude, establishing a suitable swing rate for the cutterhead, and using hooded intakes, although these conditions are rarely achieved (Herbich, 1992). Measurements around properly-operated cutterhead dredges show that suspended sediments can be confined to the immediate vicinity of the cutterhead and dissipate rapidly, with little turbidity reaching surface waters (Herbich and Brahme, 1991; LaSalle et al., 1991; Herbich, 1992). Maximum suspended sediment concentrations typically occur within 3 m above the cutterhead and decline exponentially to the sea surface (LaSalle et al., 1991). Suspended sediments in near-bottom waters may occur several hundred meters laterally from the cutterhead location (LaSalle et al., 1991).

A hopper dredge consists of one, two, or more dragarms and attached dragheads mounted on a ship-type hull or barge with hoppers to hold material dredged from the bottom (Herbich and Brahme, 1991). As the hopper dredge moves forward, sediment is hydraulically lifted through the dragarm and stored in hopper bins on the dredge (Taylor, 1990; LaSalle et al., 1991). Hopper dredging operations produce turbidity as the dragheads are pulled through bottom sediment. However, the main source of turbidity during hopper dredging operations is sediment release during hopper overflow (Herbich and Brahme, 1991; LaSalle et al., 1991; Herbich, 1992). A plume may occasionally be visible at distances of 1,200 m or more (LaSalle et al., 1991).

Much attention has been given to turbidity effects from dredging, although most reviews have concerned estuaries, embayments, and enclosed waters (e.g., Sherk and Cronin, 1970; Sherk, 1971; Sherk et al., 1975; Moore, 1977; Peddicord and McFarland, 1978; Stern and Stickle, 1978; Herbich and Brahme, 1991; LaSalle et al., 1991; Kerr, 1995; Newcombe and Jensen, 1996; Wilber and Clarke, 2001). Turbidity effects may be less important in unprotected offshore areas for several reasons. Offshore sands tend to be coarser, with less clay and silt than inshore areas. The open ocean environment also provides more dynamic physical oceanographic conditions, which minimize settling effects. In addition, offshore organisms are adapted to sediment transport processes, which create scouring, natural turbidity, and sedimentation under normal conditions. Impacts should be evaluated in light of natural variability as well as high-level disturbances associated with such events as storms, trawling, and floods (Sosnowski, 1984; Herbich, 1992). Physical disturbance of the bottom and resulting biological impacts from dredging are similar to those of storms and trawling but at a much smaller spatial scale. The following suggestions from Hughes and Connell (1999) also are instructive regarding the complexities of analyzing effects of multiple stressors (broadly defined as natural or man-made disturbances). Long-term approaches are necessary to understand biological responses to multiple stressors because studying single events in isolation can be misleading. The effects of a particular disturbance often depend critically on impacts from previous perturbations. Consequently, even the same type of recurrent stressor can have different effects at different times, depending on history. Accordingly, when the added dimension of time is considered, the distinction between single and multiple stressors becomes blurred (Hughes and Connell, 1999).

Turbidity from dredging can affect food availability for benthic organisms. Changes in light penetration and wavelengths due to turbidity can affect visibility and may be detrimental or beneficial, depending on whether an organism is predator or prey. Suspension and dispersion processes uncover and displace benthic organisms, temporarily providing extra food for bottom-feeding species (Centre for Cold Ocean Resources Engineering, 1995). Turbidity can interfere with food-gathering processes of filter feeders and organisms that feed by sight by inundation with nonnutritive particles. In addition to altered feeding rates, other biological responses to turbidity include reduced hatching success, slowed growth, abnormal development, tissue abrasion, and increased mortality (Wilber and Clarke, 2001). In general, egg and larval stages are more sensitive to turbidity effects than older life history stages.

Finally, suspension and dispersion of sediments may cause changes in sediment and water chemistry as nutrients and other substances are released from the substratum and dissolved during dredging. For aggregate mining operations using hopper dredges, the far-field visible plume contains an organic mixture of fats, lipids, and carbohydrates from organisms entrained and fragmented during the dredging process and discharged with the overflow (Coastline Surveys Limited, 1998; Newell et al., 1999). Furthermore, dredging may produce localized hypoxic or anoxic conditions in the water column due to oxygen consumption of suspended sediments (LaSalle et al., 1991). However, one should not lose track of the fact that turbidity effects are expected to be less important in unprotected offshore areas. Offshore shoals tend to be coarser with less clay and silt than inshore deposits. The open ocean environment also provides more dynamic physical oceanographic conditions, which minimize settling effects. In addition, offshore organisms are adapted to sediment transport processes, which create scouring, natural turbidity, and sedimentation under normal conditions.

3.3 SEDIMENT DEPOSITION

Suspended sediments settle and are deposited nearby dredged offshore sand borrow sites. The extent of deposition and boundaries of biological impact are dependent on the type and amount of suspended sediments and physical oceanographic characteristics of the area. Deposition of sediments can suffocate and bury benthic biota, although some mobile soft bottom organisms are able to migrate vertically to the new surface (Maurer et al., 1986; Nelson, 1988). Furthermore, sediment deposition can inhibit larvae of numerous invertebrate species that need hard surfaces to settle and develop (Thorson, 1966; Rogers, 1990).

Dredging effects are not necessarily limited to the sand borrow site alone. Far-field impacts from suspension, dispersion, and deposition of sediments during dredging can be detrimental or beneficial. Johnson and Nelson (1985) found decreases in infaunal abundances and numbers of taxa at nondredged stations, although these decreases were not as extreme as those observed in the borrow site. McCaully et al. (1977; as cited by Johnson and Nelson, 1985) also observed that dredging effects can extend to other nearby areas and noted decreases in infaunal abundances, ranging from 34% to 70% at undredged stations within 100 m of a dredged site. Conversely, benthos may show increased biodiversity downstream from dredged sites (Centre for Cold Ocean Resources Engineering, 1995). In some areas, population density and species composition of benthic invertebrates increased rapidly outside dredged sites, with the level of enhancement decreasing with increasing distance from the dredged site up to a distance of 2 km (Stephenson et al., 1978; Jones and Candy, 1981; Poiner and Kennedy, 1984). The enhancement was ascribed to release of organic nutrients from the dredge plume, a process known from other studies (Ingle, 1952; Biggs, 1968; Sherk, 1972; Oviatt et al., 1982; Coastline Surveys Limited, 1998; Newell et al., 1998, 1999). This suggestion was supported by records of nutrient releases from benthic areas during intermittent, wind-driven bottom resuspension events (Walker and O'Donnell, 1981), significant increases in water column nutrients from simulated storm events in the laboratory (Oviatt et al., 1982), and review of the literature, indicating that the response of species to resources released from sediments by periodic disturbance is a major restructuring force in infaunal communities (Thistle, 1981).

Fishing may improve temporarily down current of a dredging site and continue for some months (Centre for Cold Ocean Resources Engineering, 1995). Additional far-field impacts can occur by resuspension, redispersion, and redeposition of fine dredged materials by wave and current actions long after dredging has been completed. However, one should expect turbidity effects to be less important in unprotected offshore areas, where sand and gravel are the borrow materials. The open ocean environment also provides more dynamic oceanographic conditions, which minimize settling effects. Furthermore, offshore organisms are adapted to sediment transport processes, which create scouring, natural turbidity, and sedimentation under normal conditions.

4.0 EVALUATION OF BIOLOGICAL RESOURCES ASSOCIATED WITH SHOALS OFFSHORE OF THE MID-ATLANTIC BIGHT

(Tim D. Thibaut – Barry A. Vittor & Associates, Inc.; Barry A. Vittor – Barry A. Vittor & Associates, Inc.; David B. Snyder – CSA International, Inc.; and Kenyon C. Lindeman – Florida Institute of Technology)

Previous reviews concerning potential impacts of offshore sand mining (Research Planning, Inc. et al., 2001) suggested further investigation into the status of sand shoals as essential fish habitat (EFH) for federally managed species and their prey. At the time of that report, very little data were available on the ecological function of sand shoals for fishes or invertebrates. Since the Research Planning, Inc. et al. (2001) report was issued, information has been collected regarding fish and invertebrate utilization of sand shoals in the Mid-Atlantic Bight, particularly in the region offshore Delaware, Maryland, and New Jersey. In this section, available data are reviewed and used to characterize invertebrate and fish presence and abundance on shoals. Invertebrates relate directly to the concept of EFH because some such as longfin squid, surf clam, and ocean quahog are federally managed fishery species; and invertebrates form the forage base for benthic feeding fishes that are also federally managed. In addition, some invertebrate species form structures or engineer habitats that are used by fishes of varying life stages. In this section, invertebrates and the assemblages they form are profiled with emphasis on species composition, spatial distribution, substrate preferences, habitat forming (engineering) characteristics, capacity for recolonization following disturbance, and trophic relationships with fishes. Demersal and pelagic fish assemblages are characterized by species and life stage composition in relation to sand shoals in the Mid-Atlantic Bight. Occurrence of federally managed fish and invertebrate species designated by regional fishery management councils and field collections is also documented. To illustrate how sand shoals fit into the larger seascape with respect to ecological functions provided to fishes and during their life cycle, cross-shelf habitat matrices were constructed. Examples of cross-shelf utilization are presented and discussed for two demersal and two pelagic species. These examples along with field data on species composition are used to demonstrate that shoals contribute to spawning, feeding, shelter, and growth to maturity for numerous species managed under EFH legislation.

4.1 INVERTEBRATES

The Virginia Institute of Marine Science (VIMS) (2000) obtained physical and biological data of study area shoals and nearshore sediments during research cruises in 1998 and 1999. Grab sampling for infauna and sediments was conducted with a 0.044-m^2 Young grab. In 1998, grabs were collected across an area that included Fenwick, Weaver, and Isle of Wight shoals, and nearshore gravel and sand sheets north of the shoals near Indian River Inlet. In 1999, grab samples were collected only in the area of the shoals.

Infauna of the study area also are characteristic of assemblages across much of the western Atlantic and Gulf of Mexico (Brooks et al., 2006), mostly including annelids, predominantly polychaetes, bivalves, and crustaceans, particularly amphipods. Ubiquitous taxa occurring across the study area include nonidentified oligochaetes and rhynchocoels, and the polychaete *Spiophanes bombyx*, a highly abundant taxon distributed worldwide. Another widespread group in the study area includes the polychaetes *Aricidea ceruttii* and *A. catherinae*, *Brania wellfleetensis*, *Hemipodus roseus*, *Parapionosyllis longicirrata*, *Parougia caeca*, *Protodorvillea kefersteini*, and *Streptosyllis pettiboneae*. These polychaetes are common inhabitants of coarse sand and gravel habitats throughout the Mid-Atlantic Bight (Byrnes et al., 2000, 2003).

The raw abundance data from the 1998 to 1999 grab samples (VIMS, 2000) were obtained for this study. Spatial and temporal patterns for the infaunal community were examined using multivariate cluster analysis. The cluster analysis was performed on a similarity matrix constructed from a raw abundance data matrix consisting of taxa and samples. Except for the bivalves *Astarte* spp. and *Tellina* spp., taxa identified to a generic or higher level of identification were excluded from the matrix. After removal of incompletely identified and redundant taxa, the data matrix was constructed using those taxa that collectively contributed to 95% of the total abundance over all samples. This produced a data matrix of 57 taxa by 72 stations. To weight the contributions of common and rare taxa, raw counts of each individual taxon in a sample (n) were transformed to logarithms [$\log_{10}(n+1)$] prior to similarity analysis. The grab sample similarity matrix was generated using the Bray-Curtis similarity index (Bray and Curtis, 1957). The cluster analysis was performed using PRIMER v5 package (Clarke and Gorely, 2001).

Seven groups of stations (Groups A through G) were resolved based on similarity of infaunal assemblages. **Figure 4.1** presents the approximate locations of station groups (A through G) resolved from the cluster analysis of grab sample composition in the area of Fenwick Shoal, Isle of Wight Shoal, and Shoal A. An outlier station (X) with low abundance and taxa richness was located near the crest of Fenwick Shoal. Group A included one station on the crest of Fenwick Shoal and one station on Isle of Wight Shoal. Group B included two stations on the crest of Isle of Wight Shoal and two stations on the northeast portion of Fenwick Shoal. Group C included stations on or near the crests of Weaver and Isle of Wight shoals, and on the northeast portion of Fenwick Shoal. Group D included stations in the intershoal troughs on the lee sides of Fenwick and Weaver shoals, as well as two stations near Indian River Inlet. Group E included several stations on Weaver and Isle of Wight shoals. Group F is composed of 1998 stations primarily near the base of Fenwick Shoal and near Indian River Inlet. Group G contained the most stations of any of the seven groups, with these concentrated around the base of Fenwick Shoal, particularly on its northwest side, and extending to the nearshore area near Indian River Inlet.

Species accounting for the observed assemblage differences among groups and within groups of stations (samples) were identified using the similarity percentage breakdown (SIMPER) procedure (Clarke and Gorely, 2001). SIMPER determines the average contribution of each taxon to characterizing a sample group or discriminating between pairs of sample groups. Considering the average abundance of species accounting for at least 50% of within group similarity, Groups A, B, and C were each typified by a single taxon (**Table 4.1**).

Stations in Groups A and B yielded the fossorial amphipods *Protohaustorius wigleyi* and *Parahaustorius longimerus*, respectively, while Group C stations commonly contained the bivalve *Tellina* spp. The intershoal trough stations (Group D) were characterized by the polychaetes *Spiophanes bombyx* and *Asabellides oculata*, the bivalve *Tellina* spp., and the tube-dwelling amphipod *Unciola irrorata*. Two bivalves *Astarte* spp. and *Crenella glandula*, and the gastropod *Natica pusilla* typified Station Group E. Group F stations typically yielded polychaetes *S. bombyx* and *A. cerrutii* and the amphipod *P. wigleyi*. Stations in Group G commonly yielded various polychaetes including *Aricidea cerrutii*, *Aricidea catherinae*, *Brania wellfleetensis*, and *Aphelochaeta* sp. As indicated by their lower average similarity values, Station Groups E, F, and G were not as well defined as Groups A through D.

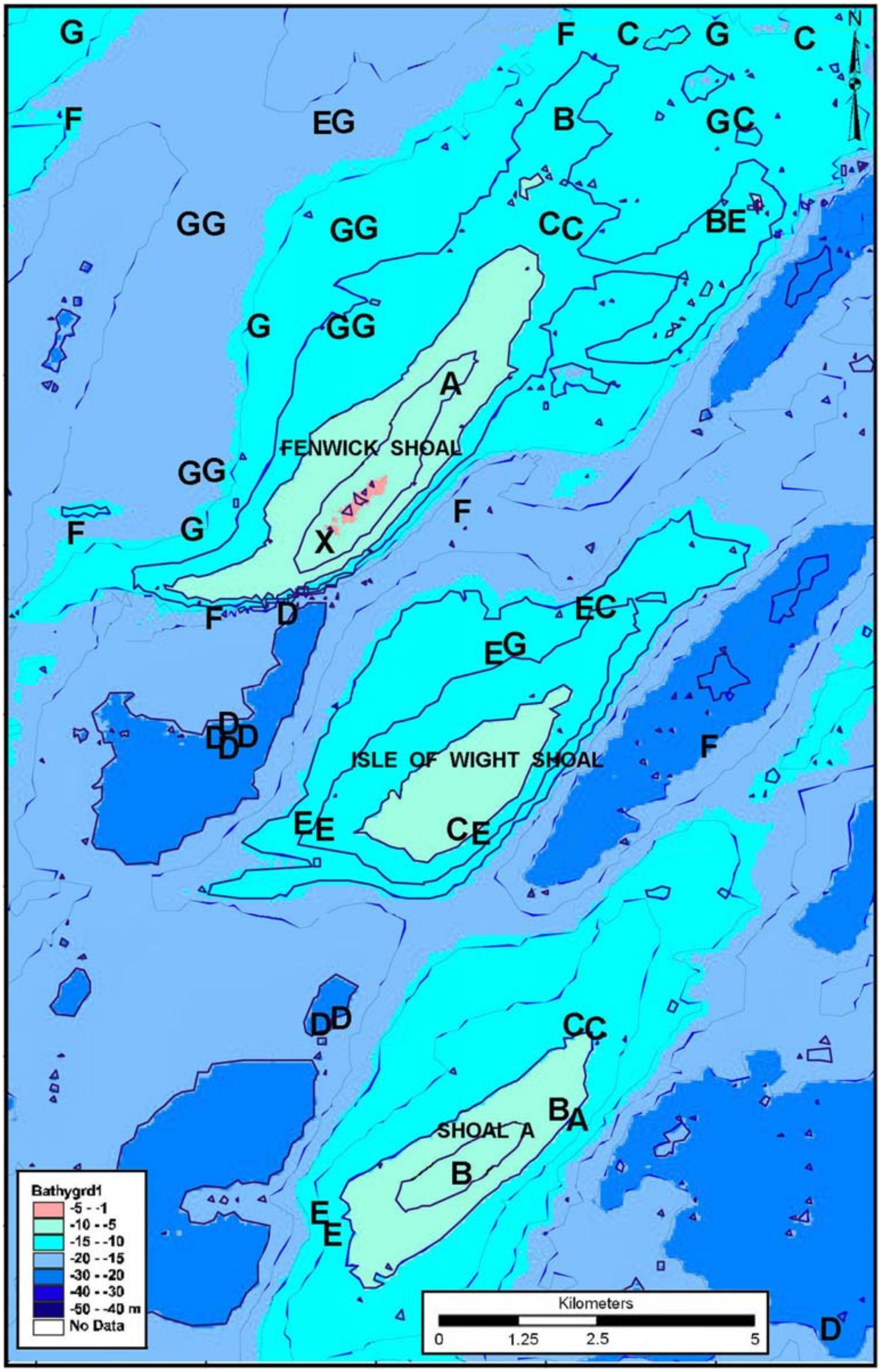


Figure 4.1. Approximate locations of station groups (A through G) resolved from cluster analysis of grab sample composition across 1998-1999 stations in the area of Fenwick Shoal (Original data, base map, and station locations adapted from Virginia Institute of Marine Science, 2000).

Table 4.1. Average abundance of infaunal species accounting for at least 50% of within-group similarity in station (sample) Groups A through G. Numbers in bold represent average similarity for each group overall.

Group	Species[1]	Average Abundance	Average Similarity
A	*Protohaustorius wigleyi* (A)	0.90	55.79 **55.79**
B	*Parahaustorius longimerus* (A)	1.71	23.19 **41.80**
C	*Tellina* spp. (B)	1.46	27.26 **43.48**
D	*Spiophanes bombyx* (P) *Asabellides oculata* (P) *Tellina* spp. (B) *Unciola irrorata* (A)	4.99 3.40 3.44 2.85	8.52 7.37 5.96 5.07 **47.20**
E	*Astarte* spp. (B) *Crenella glandula* (B) *Natica pusilla* (G)	1.97 1.81 1.14	6.35 6.31 3.75 **30.93**
F	*Spiophanes bombyx* (P) *Protohaustorius wigleyi* (A) *Aricidea cerrutii* (P)	1.57 1.32 0.92	8.41 5.96 4.64 **29.39**
G	*Aricidea cerrutii* (P) *Aricidea catherinae* (P) *Brania wellfleetensis* (P) *Aphelochaeta* sp. (P)	2.04 1.42 1.57 1.36	6.18 4.21 4.18 3.51 **35.28**

[1] A = amphipod; B = bivalve; G = gastropod; P = polychaete.

Mean number of taxa and mean individual abundance were tested for differences among the station groups resolved by cluster analysis. Raw data were entered into JMP—The Statistical Discovery Software Program for Abundance and Distribution (SAS Institute, Inc., 2007). Prior to analysis of variance (ANOVA) testing, the data were tested for distribution using a goodness of fit test to check for normality. The abundance data were determined to have a non-normality, and all samples were log-transformed prior to the ANOVA. Group D stations (inter-ridge troughs) yielded significantly greater mean individual abundance than all other station groups ($F=16.17$, $p<0.0001$). Mean number of taxa per station was also greater in Group D than all other station groups ($F=18.77$; $p<0.0001$). Further comparisons of the station group means for numbers of taxa were made using a student's t-test ($t=1.99$; $\alpha=0.05$). Station Groups A through C, which in general were located on or near shoal crests, had fewer taxa than Groups D through G (**Table 4.2**).

Table 4.2. Mean number of infaunal taxa within station groups resolved by cluster analysis.

Station Group (n)	Mean Number Taxa
A (2)	5.0
B (4)	8.0
C (10)	8.4
D (10)	29.4
E (9)	18.6
F (10)	16.6
G (26)	19.3

During the VIMS (2000) field studies, epifauna were collected during both cruises (1998 and 1999) with a 2.4-m beam trawl. The most abundant epifauna were hermit crabs (*Pagurus* spp.), portly spider crab (*Libinia emarginata*), and rock crab (*Cancer irroratus*). Other epifauna included sea stars *Asterias* spp. and sand dollars *Echinarachnius parma*, and large gastropods such as channeled whelk (*Busycon canaliculatum*) and moon snails (*Polinices* spp). Broadly distributed taxa found on and off the shoals included nudibranchs, hermit crabs, sevenspine bay shrimp (*Crangon septemspinosa*), and sea stars (VIMS, 2000).

Slacum et al. (2006) also conducted seasonal sampling of mobile epibenthic invertebrates in the study area. Four shoals (Shoal B, Shoal D, Fenwick Shoal, and Weaver Shoal) and adjacent areas of the seafloor were sampled by trawl from fall 2002 to summer 2004. Sea stars and lady crabs *Ovalipes* spp. were the most abundant invertebrate species in the fall collections, accounting for 7% of the total abundance combined. Sea stars comprised 56% of the total invertebrate abundance on the shoals and 27% at the reference sites. Lady crabs accounted for 25% of invertebrates found on the shoals and 31% of invertebrates at the reference sites. Other benthic epifauna collected in the fall were horseshoe crab (*Limulus polyphemus*), channeled whelk, and rock crab. Highly abundant benthic invertebrates of the study area seafloor and shoals included right-handed hermit crabs, sea stars, lady crab, and portly spider crab (Slacum et al., 2006).

4.2 FISHES

This section examines the current state of knowledge on the structure (species composition and relative abundance) of fish assemblages associated with sand shoals in the Mid-Atlantic Bight. Information presented here is used to make inferences regarding the functional significance of shoals as EFH in **Section 4.3**. Functional significance in this context includes use of habitat for activities such as spawning, feeding, and sheltering as opposed to energy flow within the community.

The Mid-Atlantic Bight ichthyofauna is dynamic in space and time, consisting of demersal and pelagic forms with boreal, warm temperate, and subtropical affinities (Grosslein and Azarovitz, 1982; Colvocoresses and Musick, 1984; Mahon et al., 1998). At the family level, demersal species are represented by skates (Rajiidae), dogfishes (Squalidae), requiem sharks (Carcharhinidae), searobins (Triglidae), hakes (Phycidae), anglerfishes (Lophiidae), seahorses and pipefishes (Syngnathidae), sculpins (Cottidae), sea bass (Serranidae), drums (Sciaenidae), scup (Sparidae), and flatfishes (Paralichthyidae, Pleuronectidae, Scophthalmidae).

On a broad scale, much of the spatial and temporal variations observed in Mid-Atlantic Bight demersal assemblages are driven by seasonal changes in water temperature. When water temperatures increase in the spring, warm temperate fishes move into the Mid-Atlantic Bight from the south; at the same time several cold water species migrate back to areas north of the Mid-Atlantic Bight. After shelf waters cool during fall and early winter, warm temperate species migrate back south and offshore while some of the cold temperate forms move into the area (Grosslein and Azarovitz, 1982). Typical warm temperate forms found in Mid-Atlantic Bight during spring and summer are black sea bass (*Centropristis striata*), northern searobin (*Prionotus carolinus*), scup (*Stenotomus chrysops*), spotted hake (*Urophycis regia*), and summer flounder (*Paralichthys dentatus*) (Grosslein and Azarovitz, 1982; Colvocoresses and Musick, 1984; Mahon et al., 1998). Northern or boreal species found in Mid-Atlantic Bight waters during winter and spring include goosefish (*Lophius americanus*), red hake (*Urophycis chuss*), offshore hake (*Merluccius albidus*), silver hake (*Merluccius bilinearis*), and yellowtail flounder (*Limanda ferruginea*) (Colvocoresses and Musick, 1984). The abundance and distribution of demersal fishes varies among seasons and years; however, the numerically dominant species tend to be predictable (Gabriel, 1992). In general, winter is a time of low abundance and diversity, as most species leave the area for warmer waters offshore and to the south. Some species make only local movements and may be classified as residents of the area, including dusky shark (*Carcharhinus obscurus*), lined seahorse (*Hippocampus erectus*), striped bass (*Morone saxatilis*), tilefish (*Lopholatilus chamaeleonticeps*), blackbelly rosefish (*Helicolenus dactylopterus*), summer flounder, and windowpane (*Scophthalmus aquosus*).

Pelagic species found in the Mid-Atlantic Bight include sharks (Squalidae and Carcharhinidae), herrings (Clupeidae), anchovies (Engraulidae), mackerels (Scombridae), cobia (Rachycentridae), striped bass (Moronidae), bluefish (Pomatomidae), and butterfishes (Stromateidae). All of these species form schools of varying sizes and migrate seasonally. As with the demersal fishes, most pelagic species found in the Mid-Atlantic Bight are transitory, originating in waters either to the north (Gulf of Maine or Georges Bank) or to the south (south of Cape Hatteras). Their occurrence in the Mid-Atlantic Bight is generally a response to seasonal changes in water temperature, which trigger southerly or northerly movements by species of southern or northern origin, respectively.

In concert with seasonal water temperature changes, most large-scale migrations of pelagic fishes in the Mid-Atlantic Bight are related to spawning. General patterns include 1) cross-shelf movements to offshore spawning areas; 2) movements along the shelf to southerly spawning areas; and 3) movements between coastal rivers and the coastal ocean for spawning or the reverse (diadromy). Movement of butterfish (*Peprilus triacanthus*) exemplifies the first pattern. The population migrates northward and inshore in summer then during winter months moves southward and offshore. During this time, butterfish spawn continuously from late January to at least July in the Mid-Atlantic Bight (Rotunno and Cowen, 1997). Bluefish (*Pomatomus saltatrix*), Atlantic mackerel (*Scomber scombrus*), Atlantic menhaden (*Brevoortia tyrannus*), and Atlantic herring (*Clupea harengus*) migrate following the second general pattern by moving along the coast to preferred spawning areas. For the diadromous pattern, alewife (*Alosa pseudoharengus*), blueback herring (*Alosa aestivalis*), American shad (*Alosa sapidissima*), and striped bass are anadromous, ascending from the ocean up coastal rivers to spawn in freshwater, whereas the catadromous American eel (*Anguilla rostrata*) descends coastal rivers into the ocean to spawn.

4.2.1 Fishes and Life Stages Associated with Sand Shoals

Fish assemblages associated with shoals in the Mid-Atlantic Bight region are composed of varying subsets of the regional ichthyofauna. Studies focusing strictly on fishes associated with sand shoals in the Mid-Atlantic Bight have been conducted in only two areas of the continental shelf, one off Maryland/Delaware and one off New Jersey (**Figure 1.5**). The New Jersey site consists of a single large shoal feature known as Beach Haven Ridge located ~11 km offshore of Little Egg Inlet in water depths of 2 to 19 m (**Figure 1.5**). This site was studied intensively from 1972 to 1975 when it was the candidate site for the proposed Atlantic electric power generating plant (Milstein and Thomas, 1977). During that period, Beach Haven Ridge was sampled for fishes by otter trawling monthly or biweekly. In addition, from 1973 to 1975, fish eggs and larvae were collected around the shoal using plankton nets. Data gathered during these field surveys were initially reported by Milstein and Thomas (1977) and later summarized by Able and Hagan (1995). During the 1990's, researchers from the Rutgers University Institute of Marine and Coastal Sciences, Marine Field Station in Tuckerton, New Jersey began gathering data on individual species (Lazzari and Able, 1990; McBride and Able, 1994; Able et al., 1995; Morse and Able, 1995; Campbell and Able, 1998; Duval and Able, 1998; Hales and

Able, 2001) as well as whole assemblages (Martino and Able, 2003: Able et al., 2006; Vasslides and Able, 2008) along a cross-shelf transect that extends from inside Little Egg Inlet out across Beach Haven Ridge. The data collected here are of particular value in determining habitat use because Beach Haven Ridge was located within a broader habitat gradient that extends from inshore (inside Great Bay) to the middle continental shelf. Understanding the importance of shoals as EFH will depend on the extent to which they connect with other habitats along the larger cross-shelf continuum.

The second location where fish utilization of shoals has been studied is offshore Maryland and Delaware (**Figure 4.2**). Specific shoals in the area including Fenwick Island Shoal, Weaver Shoal, Shoal B, and Shoal D were sampled by Cutter et al. (2000), Diaz et al. (2003), and Slacum et al. (2006). Rather than sampling long transects that traversed these shoals, as was the case with Beach Haven Ridge, these studies sampled across individual shoal areas using a variety of gear types including large (commercial) trawl, small otter trawl, beam trawl, gill net, towed video, and hydroacoustic imaging. Different techniques sample different components of the assemblage, and are in many respects, complementary. Slacum et al. (2006) executed a sampling design that included pairs of shoal and nonshoal reference sites to examine hypotheses regarding the use of shoals by fishes. Although systematic sampling along a cross-shelf gradient was not formally conducted at the Maryland-Delaware location, considerable information concerning inshore habitat use is available from the adjacent Delaware Bay Estuary (see review by Able et al., 2007).

The data and information from the study of these two shoal areas are reviewed with a focus on species and life stage composition. Literature and data for other habitats composing the cross-shelf continuum are also considered, including the lower estuarine environment and the middle and outer shelf. This allows shoals to be placed into the context of cross-shelf continuum of habitats, for purposes of management and EFH identification, an understanding of connections among various demersal and pelagic habitats is vital. In the following section, species composition is characterized by life stage based on available data.

4.2.2 Eggs and Larvae

Able and Hagan (1995) reported the densities and seasonality of eggs and larvae collected during the 1970’s, and Able et al. (2006) reported larvae but not eggs collected in the same area during the 1990’s. Eggs of 10 demersal taxa were collected at Beach Haven Ridge including cod (*Gadus morhua*), red hake, searobins (*Prionotus* spp.), windowpane, and sand lance (*Ammodytes* sp.) (**Table 4.3**). Of these taxa, Able and Hagan (1995) reported average number of eggs per 1,000 m^3 were highest for searobins (356), windowpane (341), and tautog (*Tautoga onitis*) (122). Eggs of all other demersal taxa averaged 20 or fewer per 1,000 m^3. Eggs of bay anchovy (*Anchoa mitchilli*), striped anchovy (*Anchoa hepsetus*), Atlantic mackerel, and Atlantic menhaden represented the pelagic group (**Table 4.4**). Bay anchovy (6,681 eggs per 1,000 m^3) and Atlantic mackerel (1,411 eggs per 1,000 m^3) contributed the highest average numbers of eggs at Beach Haven Ridge during the 1970’s (Able and Hagan, 1995). It should be noted that the order in which fishes are listed in **Tables 4.3** to **4.6** appears according to ranking based on occurrence across studies.

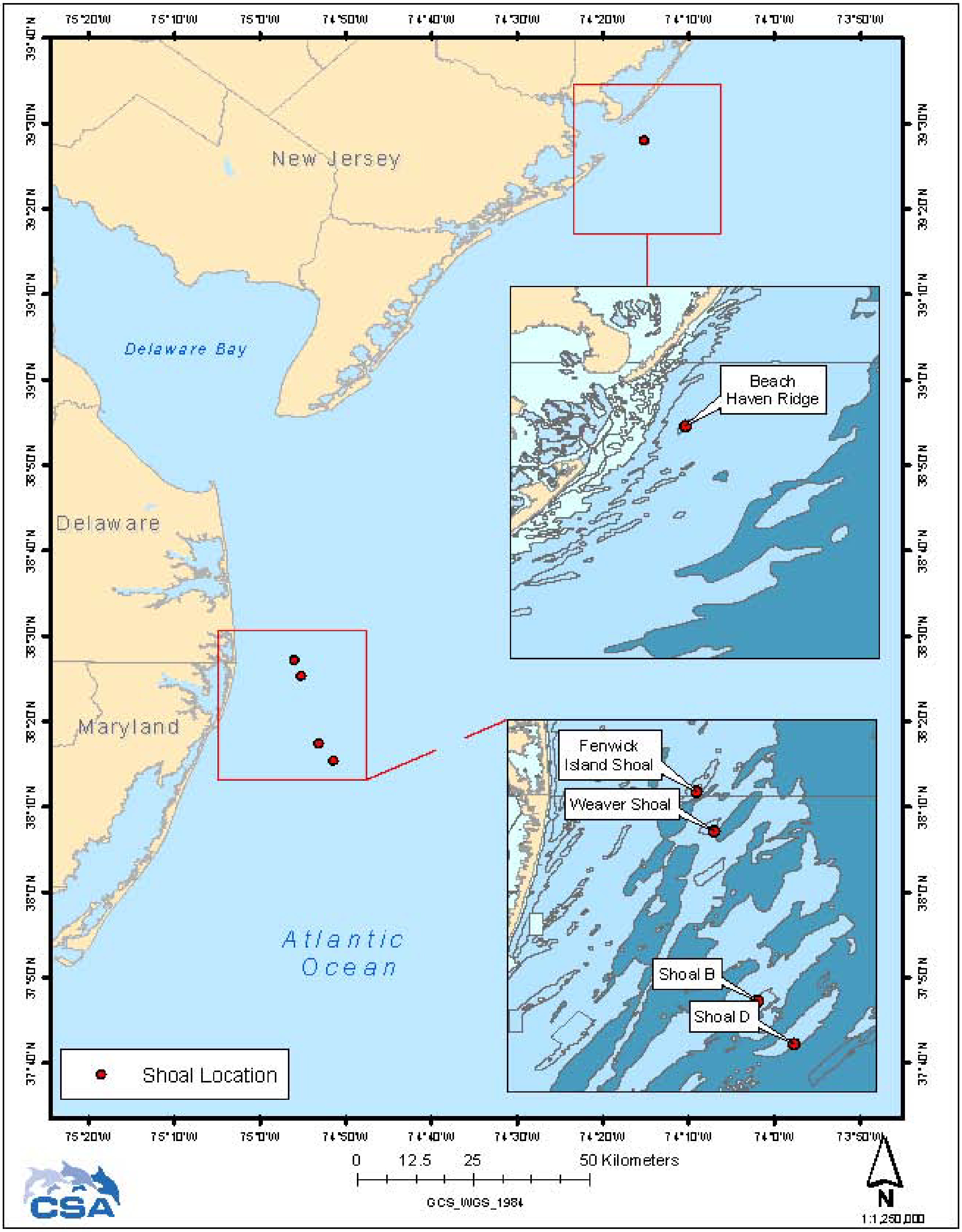


Figure 4.2. Overview of shoal sample areas.

Table 4.3. Eggs and larvae of demersal fish taxa collected in the vicinity of Beach Haven Ridge sand shoal offshore New Jersey during 1972 to 1975 and 1992 to 1995 (From: Able and Hagan, 1995; Able et al., 2006).

Scientific Name	Common Name	Eggs (1972-1975)	Larvae (1972-1975)	Larvae (1992)
Urophycis regia	Spotted hake	+	+	+
Tautoga onitis	Tautog	+	+	+
Tautolabrus adspersus	Cunner	+	+	+
Scophthalmus aquosus	Windowpane	+	+	+
Urophycis chuss	Red hake		+	+
Syngnathus fuscus	Dusky pipefish		+	+
Centropristis striata	Black sea bass		+	+
Cynoscion regalis	Weakfish		+	+
Micropogonias undulatus	Atlantic croaker		+	+
Etropus microstomus	Smallmouth flounder		+	+
Urophycis sp.	Hake	+	+	
Lophius americanus	Goosefish	+	+	
Prionotus spp.	Searobin	+	+	
Ammodytes sp.	Sand lance	+	+	
Pollachius virens	Pollack		+	
Ophidiidae	Cusk eel		+	
Hippocampus erectus	Lined seahorse		+	
Prionotus carolinus	Northern searobin			+
Menticirrhus saxatilis	Northern kingfish		+	
Astroscopus sp.	Stargazer		+	
Gobiosoma ginsburgi	Seaboard goby			+
Gobiosoma bosc	Naked goby			+
Gobiidae	Goby		+	
Lumpenus lampretaeformis	Snakeblenny		+	
Paralichthys dentatus	Summer flounder		+	
Paralichthys oblongus	Fourspot flounder		+	
Pholis gunnellus	Rock gunnel		+	
Pseudopleuronectes americanus	Winter flounder			+
Trinectes maculatus	Hogchoker		+	
Tetraodontiformes	Puffer		+	
Gadus morhua	Cod	+		
Enchelyopus cimbrius	Fourbeard rockling	+		
Limanda ferruginea	Yellowtail flounder		+	
Gadidae	Cod		+	
Myoxocephalus sp.	Sculpin		+	
Myoxocephalus octodecemspinosus	Fourhorn sculpin		+	
Sciaenidae	Drum		+	
Abudefduf saxatilis	Sergeant major		+	
Citharichthys sp.	Whiff		+	
Glyptocephalus cynoglossus	Witch flounder		+	
Total		10	34	14

Table 4.4. Eggs and larvae of pelagic fish taxa collected in the vicinity of Beach Haven Ridge sand shoal offshore New Jersey during 1972 to 1975 and 1992 to 1995 (From: Able and Hagan, 1995; Able et al., 2006).

Scientific Name	Common Name	Eggs (1972-1975)	Larvae (1972-1975)	Larvae (1992)
Brevoortia tyrannus	Atlantic menhaden	+	+	+
Anchoa hepsetus	Striped anchovy	+	+	
Anchoa mitchilli	Bay anchovy	+	+	+
Engraulidae	Anchovy		+	
Atherinidae	Silversides		+	
Pomatomus saltatrix	Bluefish		+	
Scomber scombrus	Atlantic mackerel	+		
Scomberomorus cavalla	King mackerel		+	
Peprilus triacanthus	Butterfish		+	
Total		4	8	2

Table 4.5. Adult and juvenile demersal fishes collected around sand shoals offshore New Jersey, Delaware, and Maryland (Sources: Able and Hagan, 1995; Martino and Able, 2003; Able et al., 2006; Slacum et al., 2006; Vasslides and Able, 2008).

Scientific Name	Common Name	Beach Haven Ridge, NJ (1972-1975)	Beach Haven Ridge, NJ (1992)	Beach Haven Ridge, NJ (1997-1999)	Fenwick Island Shoal	Weaver Shoal	Shoal B	Shoal D
Leucoraja erinacea	Little skate	+	+	+	+	+	+	+
Raja eglanteria	Clearnose skate	+	+	+	+	+	+	+
Urophycis regia	Spotted hake	+	+	+	+	+	+	+
Prionotus carolinus	Northern searobin	+	+	+	+	+	+	+
Stenotomus chrysops	Scup	+	+	+	+	+	+	+
Scophthalmus aquosus	Windowpane	+	+	+	+	+	+	+
Etropus microstomus	Smallmouth flounder	+	+	+	+	+	+	+
Paralichthys dentatus	Summer flounder	+	+	+	+	+	+	+
Leucoraja ocellata	Winter skate	+	+		+	+	+	+
Prionotus evolans	Striped searobin	+	+	+	+	+	+	
Micropogonias undulatus	Atlantic croaker	+	+	+	+	+		+
Synodus foetens	Inshore lizardfish	+	+	+	+	+		
Dipturus laevis	Barndoor skate		+		+	+	+	
Myliobatis freminvillei	Bullnose ray	+	+		+	+		
Merluccius bilinearis	Silver hake	+	+				+	+
Hippocampus erectus	Lined seahorse		+	+	+	+		
Cynoscion regalis	Weakfish	+		+	+	+		
Ammodytes americanus	American sand lance	+	+		+		+	
Urophycis tenuis	White hake	+		+	+			
Ophidion marginatum	Striped cusk eel	+		+		+		
Syngnathus fuscus	Dusky pipefish	+		+	+			
Bairdiella chrysoura	Silver perch	+		+	+			

Table 4.5. (Continued).

Scientific Name	Common Name	Beach Haven Ridge, NJ (1972-1975)	Beach Haven Ridge, NJ (1992)	Beach Haven Ridge, NJ (1997-1999)	Fenwick Island Shoal	Weaver Shoal	Shoal B	Shoal D
Pseudopleuronectes americanus	Winter flounder	+		+	+			
Gymnura micrura	Smooth butterfly ray	+	+					
Lophius americanus	Goosefish	+				+		
Centropristis striata	Black sea bass			+		+		
Leiostomus xanthurus	Spot	+			+			
Menticirrhus saxatilis	Northern kingfish			+		+		
Astroscopus guttatus	Northern stargazer		+		+			
Gobiosoma ginsburgi	Seaboard goby	+		+				
Limanda ferruginea	Yellowtail flounder	+			+			
Sphoeroides maculatus	Northern puffer		+	+				
Squatina dumeril	Atlantic angel shark		+					
Dasyatis centroura	Roughtail stingray		+					
Dasyatis say	Bluntnose stingray	+						
Gymnura altavela	Spiny butterfly ray	+						
Rhinoptera bonasus	Cownose ray		+					
Acipenser oxyrhynchus	Atlantic sturgeon	+						
Conger oceanicus	Conger eel					+		
Trachinocephalus myops	Snakefish	+						
Melanogrammus aeglefinus	Haddock	+						
Urophycis chuss	Red hake			+				
Enchelyopus cimbrius	Fourbeard rockling					+		
Opsanus tau	Oyster toadfish	+						
Apeltes quadracus	Fourspine stickleback	+						
Gasterosteus aculeatus	Threespine stickleback	+						
Fistularia tabacaria	Bluespotted cornetfish	+						
Hemitripterus americanus	Sea raven	+						
Myoxocephalus aenaeus	Grubby	+						
Liparis inquilinus	Inquiline snailfish	+						
Mycteroperca microlepis	Gag	+						
Pristigenys alta	Short bigeye	+						
Larimus fasciatus	Banded drum	+						
Pogonias cromis	Black drum	+						
Pseudupeneus maculatus	Spotted goatfish	+						
Tautoga onitis	Tautog			+				
Zoarces americanus	Ocean pout	+						
Hypsoblennius hentz	Feather blenny	+						
Gobiosoma bosc	Naked goby	+						
Citharichthys spilopterus	Bay whiff	+						
Paralichthys oblongus	Fourspot flounder	+						
Trinectes maculatus	Hogchoker	+						
Monacanthus hispidus	Planehead filefish	+						
Chilomycterus schoepfii	Striped burrfish			+				
Total		50	23	25	24	22	13	11

Table 4.6. Adult and juvenile pelagic fishes collected around sand shoals offshore New Jersey, Delaware, and Maryland (From: Able and Hagan, 1995; Martino and Able, 2003; Able et al., 2006; Slacum et al., 2006; Vasslides and Able, 2008).

Scientific Name	Common Name	Beach Haven Ridge, NJ (1972-1975)	Beach Haven Ridge, NJ (1992)	Beach Haven Ridge, NJ (1997)	Fenwick Island Shoal	Weaver Shoal	Shoal B	Shoal D
Squalus acanthias	Spiny dogfish	+	+		+	+	+	+
Mustelus canis	Smooth dogfish	+	+		+	+	+	+
Pomatomus saltatrix	Bluefish		+	+	+	+	+	+
Peprilus triacanthus	Butterfish		+	+	+	+	+	+
Rhizoprionodon terraenovae	Atlantic sharpnose shark		+		+	+	+	+
Alosa pseudoharengus	Alewife	+	+		+			+
Alosa sapidissima	American shad	+	+		+	+		
Brevoortia tyrannus	Atlantic menhaden		+		+	+		+
Menidia menidia	Atlantic silverside		+		+	+		+
Morone saxatilis	Striped bass		+		+	+		+
Caranx crysos	Blue runner	+	+	+			+	
Scomberomorus maculatus	Spanish mackerel		+		+		+	+
Carcharhinus plumbeus	Sandbar shark		+			+	+	
Clupea harengus	Atlantic herring		+	+			+	
Anchoa hepsetus	Striped anchovy		+	+		+		
Anchoa mitchilli	Bay anchovy	+		+		+		
Alopias vulpinus	Thresher shark	+	+					
Alosa aestivalis	Blueback herring	+					+	
Rachycentron canadum	Cobia		+			+		
Decapterus punctatus	Round scad	+		+				
Sarda sarda	Atlantic bonito		+					+
Scomber scombrus	Atlantic mackerel		+		+			
Carcharhinus obscurus	Dusky shark		+					
Alosa mediocris	Hickory shad		+					
Etrumeus teres	Round herring	+						
Engraulis eurystole	Silver anchovy				+			
Morone americana	White bass	+						
Seriola zonata	Banded rudderfish			+				
Sphyraena borealis	Northern sennet	+						
Peprilus alepidotus	Harvestfish		+					
Total		12	21	8	13	13	10	11

The larvae of 34 demersal taxa occurred in plankton net samples over a 3-year period from Beach Haven Ridge in 1970's (**Table 4.3**). Sand lance numerically dominated the catches, averaging 1,008 larvae per 1,000 m^3, followed by gobies (43 larvae per 1,000 m^3) and searobins (*Prionotus*) (16 larvae per 1,000 m^3) (Able and Hagan, 1995). During the 1990's, Able et al. (2006) collected 14 larvae of demersal taxa including 10 previously reported by Able and Hagan (1995). These included larvae of spotted hake, tautog, cunner (*Tautolabrus adspersus*), black sea bass, seaboard goby (*Gobiosoma ginsburgi*), Atlantic croaker (*Micropogonias undulatus*), windowpane, searobins (*Prionotus*), and red hake from around Beach Haven Ridge (**Table 4.3**). The most abundant taxa collected in the 1990's were windowpane (7.9 larvae per 1,000 m^3), smallmouth flounder (*Etropus microstomus*) (7.8 larvae per 1,000 m^3), weakfish (*Cynoscion regalis*) (4.9 larvae per 1,000 m^3), and dusky pipefish (*Syngnathus fuscus*) (3.5 larvae per 1,000 m^3). Most of the early (preflexion) larvae collected by Able et al. (2006) were taken in coastal ocean waters, not in the estuary.

Larvae of eight pelagic taxa were collected during the 1970's near Beach Haven Ridge (Able and Hagan, 1995) (**Table 4.4**). Averaging 847 larvae per 1,000 m^3, anchovies were by far the most abundantly collected larval taxon (Able and Hagan, 1995). During the 1990's sampling, only two taxa were reported as larvae (**Table 4.4**): bay anchovy (66.2 larvae per 1,000 m^3), unidentified anchovies (359.8 per 1,000 m^3), and Atlantic menhaden (13.2 larvae per 1,000 m^3) (Able et al., 2006).

4.2.3 Juveniles and Adults

Juvenile and adult stage species are treated together in this subsection because researchers did not always distinguish the two in their data reports. The combined studies reported 64 demersal species from 36 families. The most species rich families were skates, hakes, drums, and sand flounders. Eight species were collected during all studies from five shoal areas (**Table 4.5**). These were little skate (*Leucoraja erinacea*), clearnose skate (*Raja eglanteria*), spotted hake, northern searobin, scup, windowpane, smallmouth flounder, and summer flounder.

The Beach Haven Ridge trawl sampling from 1972 to 1975 produced 50 demersal species (Able and Hagan, 1995) (**Table 4.5**). During unseasonably warm periods, a number of species originating with more subtropical affinities, including bluespotted cornetfish (*Fistularia tabacaria*), short bigeye (*Pristigenys alta*), gag (*Mycteroperca microlepis*), round scad (*Decapterus punctatus*), goatfish (Mullidae), and gray snapper (*Lutjanus griseus*), were collected (Milstein and Thomas, 1976). Many of these tropical and subtropical species do not survive following the onset of low winter temperatures (e.g., McBride and Able, 1998), but there is evidence that some warm temperate species are expanding their range into the Mid-Atlantic Bight in response to climate change (Hare and Able, 2007).

During the 1990's, the most common juvenile and adult fishes collected at Beach Haven Ridge (Martino and Able, 2003; Vasslides and Able, 2008) were searobins, gobies, black sea bass, and drums. Most of the juveniles reported by Able et al. (2006) were found in both estuarine and coastal ocean waters. The sampling distinguished species that were seasonal from those that were year-round residents. Seasonal species included boreal (cold temperate) forms only present during winter and spring, including herrings, hakes, sticklebacks, and sculpins. Species collected year-round were silver hake, spotted hake, smallmouth flounder, and windowpane.

The shoals off Maryland and Delaware were sampled during spring, summer, fall, and winter for 2 years using trawls (small and large), gill nets, and hydroacoustics (Slacum et al., 2006).

A total of 57 species was collected from all sampling sites including shoals and nonshoal reference sites (Slacum et al., 2006). Fenwick Island Shoal supported the most species followed by Weaver Shoal. The average number of individuals collected by trawl varied with the size of the gear and season. Catch per unit effort on the shoals by the smaller trawl ranged from 0.52 on Shoal D to 129.4 on Weaver Shoal. Average catches by the larger commercial trawl ranged from 10.97 at Shoal D to 1,577 individuals at Weaver Shoal. Catches were highest during the spring sampling period. Winter skate (*Leucoraja ocellata*), scup, and windowpane were the most abundant species collected overall by the larger trawl. In general, the lowest catches were made during winter and highest in fall and spring. Although much of the statistical analyses of the net data indicated no significant difference between shoals and nonshoal reference areas, individual samples demonstrated considerable variability. For example, 1,225 (catch per unit of effort 583.49) striped bass were collected in one tow of the large at Fenwick Island Shoal during fall of 2003, and 3,336.74 (catch per unit effort) scup were collected by large trawl a Fenwick Shoal during spring of 2004.

Slacum et al. (2006) deployed gill nets to sample the water column for pelagic species. Twenty-one fish species were collected by gill net across the shoals. Smooth (*Mustelus canis*) and spiny (*Squalus acanthias*) dogfish were the most abundant species collected. Gill net catches ranged from 0 fish at Shoal B, Shoal D, and Weaver Shoal to 46.74 individuals at Shoal B and were highest during summer sampling periods.

Pelagic fishes collected around the Maryland-Delaware shoals (**Table 4.6**) included herrings such as alewife, American shad, blueback herring, Atlantic herring, and Atlantic menhaden; mackerels including Spanish mackerel (*Scomberomorus maculatus*) and Atlantic mackerel; bluefish; cobia (*Rachycentron canadum*); and butterfish. Coastal sharks were represented by spiny dogfish, Atlantic sharpnose shark (*Rhizoprionodon terraenovae*), dusky shark, and sandbar shark (*Carcharhinus plumbeus*) (Slacum et al., 2006). Milstein (1981) reported the size and abundance of juvenile herrings (*Alosa* spp.) in the vicinity of Beach Haven Ridge.

Slacum et al. (2006) also employed hydroacoustic echosounding technology to estimate total biomass and abundance of pelagic and demersal fishes associated with the shoals. This approach is effective in mapping distributions of fish schools (or single larger individuals) over a spatial grid surveyed with a hydroacoustic transducer and will sample fishes that normally avoid conventional bottom trawl gear. Sampling conducted at night found aggregations of fishes were present during nighttime hours but not as much during the day.

In summary, a diverse array of species and their life stages have been collected and documented in association with sand shoals in two areas of the Mid-Atlantic Bight continental shelf. There are several demersal and pelagic species that affiliate with shoals as well as other habitats along the cross-shelf continuum. From egg and larval data, it appears that several species spawn in the vicinity of shoals. Juvenile and adult occurrences also indicate that shoals provide habitat for several species. It is likely that these species are seeking food, shelter, orientation, or a break from the currents when they associate with sand shoals. Presence, abundance, and species richness are partial indicators of habitat quality; however, additional information on species-specific growth rates, reproductive output, feeding habits, and movements is needed to provide adequate assessments of habitat quality.

4.3 INTERACTIONS BETWEEN INVERTEBRATES AND FISHES

4.3.1 Trophic Relationships

Regardless of the level of complexity, most marine food webs share fundamental structural and ordering characteristics with those of estuarine, fresh water, and terrestrial systems (Dunne et al., 2004). Dredging removes benthic invertebrates along with sediments, and therefore pathways of trophic energy flow and reproductive potential are removed from mined sites until after recolonization occurs. Link (2002) suggested that marine food webs are complex due to their openness, lack of specialists, long lifespans, and large size changes across the life histories of many species. Reise (2002), however, suggested that benthic communities in marine sediments have a simple trophic structure in general, but in combination with bioengineering and bioturbation these phenomena result in a complex "habitat web."

Benthic invertebrates have an important role in transferring energy from organic detritus to higher trophic levels (Newell et al., 1998) and invertivory is the primary trophic feature of most benthic and many pelagic fishes. The study area is similar to inner shelf systems, with generally coarse sediments and a low standing stock of organic carbon. The ultimate source of organic detritus in oceanic surface waters is biological production (Suess, 1980). Deposition of particulate organic matter is subject to seasonal variations caused by the phytoplankton annual productivity cycle (Graff, 1992), and detrital inputs are important for provision of organic matter to the benthos (Levinton and Kelaher, 2004). Detritus may increase system stability and persistence through substantial effects on trophic structure and biodiversity (Moore et al., 2004).

There are strong correlations between primary production and the standing crop and production of benthic macrofauna in phytoplankton-dominated marine ecosystems (Nixon and Buckley, 2002). Low amounts of organic enrichment may limit secondary production in open shelf sediments (Day et al., 1971; Hanson et al., 1979; Tenore, 1985). Howe et al. (1988) estimated secondary production of benthic mollusks at a Delaware Bay site and two coastal Delaware sites and found decreasing production from the estuary to the inner shelf, with total mollusk production markedly lower at an offshore station compared to inshore locations.

In the western North Atlantic, bivalves contribute the greatest percentage of total infaunal biomass, accounting for between 58% and 65% of biomass in depths less than 100 m (Wigley and Theroux, 1981). Bivalves were the major contributors to biomass during the 1998 to 1999 cruises in the study area (VIMS, 2000), with 8 taxa in the top 24 for total biomass. Wet weight biomass was dominated by surf clams (*Spisula solidissima*), which represented 65% of the total biomass for both cruises. After bivalves, the primary contributors to study area biomass include several polychaetes and amphipods. High biomass polychaetes are predominantly associated with intershoal swales, such as those on the lee (south) side of Weaver Shoal. Amphipods are more widespread, with mostly tube-dwellers associated with swales and burrowing amphipods on the shoals. Overall, swales and troughs tend to have greater benthic macrofaunal density and biomass compared with areas without depressions (Boesch, 1979; Barros et al., 2004).

In addition to surf clams and burrowing amphipods, common macrobenthos inhabiting potential mining sites of the study area include tunicates, sand dollars, mussels, and other suspension-feeding benthos, as well as various annelids. Many of these benthic invertebrates are prey for motile epifauna and demersal fishes. Juvenile surf clams are consumed by common shoal taxa such as moon snails, spider crabs (*Lilbinia* spp.), rock crabs (*Cancer* spp.), lady crabs (*Ovalipes ocellatus*) (Franz, 1977; Fay et al., 1983; Dietl and Alexander, 1997), and sea stars (Meyer et al., 1981). Larger clams are less commonly consumed due to their thicker shells. Fish predators of surf clams typically consume smaller clams (Ropes, 1980).

There is relatively little information on direct fish feeding on shoal invertebrates, though basic patterns may be inferred from related information (e.g., Able and Fahay, 1998). Weaver Shoal can undergo substantial diel shifts in pelagic fish fauna, whereas some smaller shoals may not (Slacum et al., 2006). These day-night shifts in ichthyofaunal assemblages may be associated in part with feeding, but mechanisms are unstudied.

Bottom-dwelling decapods are among the chief consumers of the benthos, and in general are opportunistic predators. Rock crabs and lady crabs feed on the most commonly abundant invertebrates of coastal sediments, including polychaetes, bivalves, echinoderms, and smaller crustaceans (Stehlik, 1993). Blue crabs (*Callinectes sapidus*) are also opportunistic feeders, and consume locally abundant infauna, epifauna, and fish (Tagatz, 1968). Sevenspine bay shrimp (*Crangon septemspinosa*) feed on mollusks, arthropods, annelids, and fish (Wilcox and Jeffries, 1974; Witting and Able, 1993; Bertram and Leggett, 1994).

Some larval and juvenile fishes are vulnerable to decapod predation. For example, larval and recently settled winter flounder (Bertram and Leggett, 1994; Witting and Able, 1995) and summer flounder (Witting and Able, 1993) may suffer significant levels of mortality due to predation by sevenspine bay shrimp. Typically, there is also substantial predation upon crustaceans by older life stages of fishes such as summer flounder (Able and Kaiser, 1994).

Common decapods of the study area are a primary component of the diets of demersal fishes. In the Mid-Atlantic Bight, sevenspine bay shrimp, portunid crabs (lady crab and blue crab), and rock crabs are important prey for fishes (Bowman et al., 2000). Decapods and amphipod crustaceans were the most common food items identified in the stomachs of fishes collected in the study area (VIMS, 2000). Lady crabs are an important component in the diet of fishes such as cobia (Arendt et al., 2001).

Because decapods are opportunistic predators of infauna, and in turn are important in the diet of higher predators, they may provide an important link between benthic secondary production and higher trophic levels on the inner shelf. Sevenspine bay shrimp is a numerically dominant species inhabiting coastal and estuarine waters (Heck and Thoman, 1984), and is known to play an important role in food energy transfer in tidal marsh estuarine ecosystems (Haefner, 1979). Similarly, blue crabs play a major role in energy transfer within estuaries (Baird and Ulanowicz, 1989). Bay shrimp, blue crabs, and other highly motile decapods of the study area may serve a similar role in shoal systems.

4.3.2 Habitat Engineers

Physical ecosystem engineering (habitat engineers) by organisms is the physical modification, maintenance, or creation of habitats (Jones et al., 1994, 1997). Ecological effects of habitat engineering occur because the physical state changes directly or indirectly control resources used by other species. According to Reise (2002), bioengineered structures and engineering processes generate dynamic and complex habitat-mediated interaction webs, affecting and meshed into the trophic web, which they may rival in overall importance in the self-structuring of the benthos. Reise (2002) further suggested that in near-shore sediments, biogenic habitat transformations pervade all community interactions.

Organisms that provide structural complexity are generally found to enrich local biodiversity compared to nonstructured habitat (Heck and Wetstone, 1977; Summerson and Peterson, 1984; Thompson et al., 1996; Tolley and Volety, 2005; Cocito, 2006; Eriksson et al., 2006; Borthagaray and Carranza, 2007; Voultsiadou et al., 2007; Van Hoey et al., 2008) and may also increase biomass production (Tolley and Volety, 2005; Eriksson et al., 2006). The structure of spatially complex habitats may mitigate predator-prey interactions by providing places for prey to hide or escape predators, though attracting and concentrating predators in some cases may negate refuge value in some circumstances (Grabowski and Powers, 2004).

In shallow subtidal sediments, community structure is determined largely by disturbances and physical stresses (Probert, 1984; Hall, 1994; Thrush et al., 1996). Patchiness in the distribution of marine sedimentary habitats may be important in maintaining community patterns of diversity, and the spatial distribution and size of habitats in an open shelf landscape play an important role in the functioning and structure of benthic communities (Thorson, 1957; Abele and Walters, 1979; Andrew and Mapstone, 1987; Morrisey et al., 1992; Hall et al., 1994; Zajac et al., 1998, 2003; Pineda, 2000; Thrush et al., 2000, 2005; Levinton and Kelaher, 2004). Bioengineered structures create variation in resources in otherwise featureless substrata, and thereby influence the distribution of associated species (Jones et al., 1994, 1997).

Small resident species of juvenile fishes and motile epifauna are often found in high abundances in biogenic habitats (Summerson and Peterson, 1984). Intershoal swales and other areas to the southwest and southeast of Weaver Shoal support tube-building polychaetes (*Asabellides* and *Diopatra*) and other surface-oriented infauna and epifauna (VIMS, 2000). Compared to higher areas on the shoals, small crabs are most abundant in these habitats with biogenic structure (Diaz et al., 2003). Polychaete tube mats are important sources of microhabitat structure and supported two to four times more fishes (Diaz et al., 2003). On Fenwick and Weaver Shoals, the incidence of fishes was four times higher in areas with large bedforms (sand waves >30 cm wavelength and approximately 10 cm crest height) (Diaz et al., 2003).

4.3.3 Bioturbation

Bioturbation is the displacement and mixing of sediment particles by benthic fauna. Faunal activities, such as burrowing, ingestion and defecation of sediment grains, construction and maintenance of galleries, infilling of abandoned dwellings, and feeding, displace sediment grains and mix the sediment matrix (Hall, 1994). Pearson (2001) noted that bioturbation may in fact be more important than physical forces in particle recycling and mixing detritus within the sediment matrix.

Biological disturbances rework sediments, causing changes to habitat properties such as sediment stability and permeability, and influencing community patterns (Jones and Jago, 1993; Thrush et al., 1996). Foraging by predators may also mix and displace sediments (Woodin, 1981; Oliver and Slattery, 1985; Hall et al., 1991). The sediment-water interface increases in area as a result of bioturbation, affecting chemical fluxes and exchange between the sediment and water column. Some organisms may further enhance chemical exchange by flushing their burrows with the overlying waters, a process termed bio-irrigation.

Burrowing and irrigation activity of infauna can distribute oxygen much deeper into the sediment (Rhoads et al., 1977). Bioturbation will to some degree promote benthic recovery after dredging. Sediment surfaces exposed by dredging typically are oxygen poor, and in addition to pore water flushing due to boundary shear flow, the activities of fauna such as burrowing nereidid polychaetes (Kristensen et al., 1985) and subsurface irrigating fauna (Forster and Graf, 1995) help improve habitat quality.

4.4 RECOLONIZATION

4.4.1 Settlement Patterns

Active selection of a settling site is common in invertebrate larvae, which respond to physical and chemical indicators of habitat suitability (Butman et al., 1988; Pawlik, 1992; Tamburri et al., 1996; Abelson and Denny, 1997; Snelgrove et al., 2001; Ullberg and Ólafsson, 2004; Duchêne, 2004). Larvae may use a complex suite of chemical and sedimentological cues when making a decision to accept or reject a settlement site (Eckman, 1996; Qian, 1999), including factors such as sediment grain size, presence of adults, and organic content. For both fishes and invertebrates, habitats must have some minimal suitability appropriate to metamorphosing stages to trigger settlement (Thorson, 1957; Butman, 1987; Able and Fahay, 1998; Sullivan et al., 2000).

Since marine larvae are generally weak swimmers (Mileikovsky, 1973; Chia et al., 1984), large-scale transport of larvae is due to passive motion under most prevailing turbulent flow conditions (Butman, 1987; Shanks, 1995; Abelson and Denny, 1997). Turbulent processes and tidal fronts concentrate and entrain pelagic larvae (Clancy and Epifanio, 1988; Hongguang and Grassle, 2004). Delivery of pelagic larvae to particular locations across large areas of the open shelf may depend particularly on hydrographic forces that transport larval patches present in the water column. The primary agents of larval transport in the Mid-Atlantic Bight include alongshore wind stress and density differences between water masses (Hare and Cowen, 1996; Epifanio and Garvine, 2001). In the Weaver Shoal study area, this interaction results in a set of buoyancy-driven currents that flow southward in a narrow band along to the coast, and strongest just south of major estuaries (Garvine, 1987; Epifanio and Garvine, 2001). As river discharge from the Delaware estuary diminishes in the late summer, the effect of winds (relative to buoyancy forcing) on larval transport may increase (Natunewicz et al., 2001).

Over smaller spatial scales, bottom shear slows hydrodynamic flow, increasing the importance of maneuverability, the ability to detect settlement cues, and settlement itself (Scheltema, 1986; Butman, 1987; Eckman, 1996; Abelson and Denny, 1997; Qian, 1999; Pineda, 2000). Exploratory larval behavior is more important over small spatial and temporal scales immediately preceding or during initial contact with the substratum. Changes in benthic boundary layer flow have potential to alter small-scale patterns of larval behavior and settlement (Scheltema, 1986; Butman, 1987; Eckman et al., 1990; Jonsson et al., 1991; Gross et al., 1992; Snelgrove, 1994; Snelgrove and Butman, 1994; Abelson and Denny, 1997; Snelgrove et al., 1998; Crimaldi et al., 2002; Lindegarth et al., 2002). Settlement cues that initiate termination of planktonic life must operate under the hydrodynamic conditions experienced by a larva while in the bottom boundary layer (Scheltema, 1986; Eckman, 1996).

Though benthic larvae respond to specific habitat cues, the availability and abundance of larvae may sometimes be more important than habitat characteristics in determining patterns of settlement (Snelgrove et al., 2001). However, the relationship between larval availability, dispersal, and recruitment is complex, and settlement and recruitment may not correlate directly with larval supply (Bhaud, 1998; Pineda, 2000). Moreover, rather than larval supply or settlement rates, post-settlement migration, differential vulnerability to predation, and other ecological processes may have strong controlling influences on adult distributions and community patterns (Ólafsson et al., 1994; Gosselin and Qian, 1997; Bhaud, 1998; Palma et al., 1999). The relative importance of temporal and spatial variability in larval abundance, settlement, and early survival in controlling observed patterns in adult populations is likely to vary among locations, times, habitat types, and species (Butman, 1987; Ólafsson et al., 1994).

4.4.2 Recovery Dynamics

The benthic community often recovers rapidly in offshore dredged sites (Johnson and Nelson, 1985; Jutte et al., 2002; Posey and Alphin, 2002) but this depends in part on a wide array of criteria for what recovery is and how to measure it (Wilbur and Stern, 1992; Nelson, 1993). Inner shelf sediments support fauna that are adapted to periodic disturbance (Day et al., 1971; Pratt, 1973). Faunal recovery in disturbed sediments is most rapid in less physically stable habitats (Collie et al., 2000). Resiliency of invertebrate assemblages in marine subtidal sediments is due primarily to the opportunistic life histories and behaviors inherent in many benthic populations (Newell et al., 1998; Posey and Alphin, 2002).

There may be short-term physical effects of dredging related to degraded hydrology in excavated sites. Anoxic, hypoxic, or noxious conditions may inhibit faunal colonization of recently dredged sites. Significantly, dredging can cause changes in surface (sediment-water interface) and subsurface (pore water) oxygen concentrations. Since marine sediments are anoxic at some depth below the sediment-water interface (Fenchel, 1969), dredging often removes the upper, oxygenated strata. In addition, naturally occurring sulfide and ammonia may be mobilized by dredging (Mayer et al., 1991). Sulfide is naturally present in the top layers of marine sediments, and is toxic to a variety of benthic animals (Wang and Chapman, 1998).

Post-larvae have been shown to avoid recently disturbed sediments (Woodin et al., 1995; Marinelli and Woodin, 2002). Woodin et al. (1995) found that recently settled juveniles of the polychaetes *Nereis vexillosa* and *Arenicola cristata* discriminate between undisturbed sediments and recently disturbed substrata with subsurface sediment exposed, such as that which occurs with dredging. Juvenile *N. vexillosa* and *A. cristata* rejected or were significantly slower to burrow into disturbed sediment surfaces. Processes determining pore-water oxygen composition may drive the acceptability of sediments to new recruits (Marinelli and Woodin, 2002).

Mobilized contaminants like ammonia may provide negative cues of habitat suitability, causing benthos to avoid recently disturbed sites (Engstrom and Marinelli, 2005). Hypoxia, anoxia, and chemical contamination may inhibit faunal recruitment for some period of time after cessation of dredging, until substratum reworking and subsurface and near-bottom shear flow ameliorate adverse hydrologic conditions. Because of the dynamic wave and current energies of the study area, hydrologic impairment in a mined site likely would be of short duration following cessation of dredging. In coarse sediment habitats with strong currents and wave action, subsurface hydrology provides deeper oxygenation and more rapid flushing of interstitial water (Revsbech et al., 1980).

Infauna and epifauna recruit into dredged sites via larval settlement and post-larval migration across the seabed. Typically the initial stages of recolonization primarily involve opportunistic species, and longer-lived taxa colonize after the initial stages. Longer time frames are usually required for benthic assemblage composition of a dredged site to attain similarity with adjacent nondisturbed areas. The nature of biological recovery, including the speed of colonization and benthic assemblage composition, will depend in large measure on physical characteristics of a site after dredging and species-specific patterns of larval supply, both aspects often subject to high temporal variation.

Compared to intertidal and hard bottom benthos, invertebrate larvae of soft sediment subtidal systems have a higher proportion of planktonic forms capable of an extended period of viability (Grantham et al., 2003), and potentially may be dispersed across large spatial scales. It is not clear, however, that long-range transport of larval recruits is necessary for benthic community recovery in mined sites on the inner shelf.

Many invertebrate larval forms are adapted for rapid metamorphosis and short-range dispersal. Marine-invertebrate phyla share the developmental trait of metamorphic competence, a state in which nearly all requisite juvenile characters are present in the larva prior to settlement (Hadfield et al., 2001). Competence and consequent rapid metamorphosis in marine invertebrate larvae are conjectured to have arisen because they allow larvae to continue to swim and feed in the planktonic realm while simultaneously permitting extremely fast morphological transition from larval locomotory and feeding modes to a different set of such modes that are adaptive to life on the sea bottom (Hadfield et al., 2001).

Marine invertebrate larvae are broadly classified as either planktotrophic or lecithotrophic. Planktotrophic larvae feed and mature in the water column, and have potential for long-distance dispersal. Lecithotrophic larvae are nonfeeding with comparatively limited dispersal. A number of larval forms do not fit neatly into either of these two categories (Hines, 1986a), however, and recent descriptions of larval development and life histories suggest that facultative feeders and other intermediate forms are not as rare as commonly assumed (Allen and Pernet, 2007). Moreover, some benthic invertebrates commonly exhibit poecilogony, which is the presence of variable larval development modes within a species. Groups exhibiting poecilogony include common study area inhabitants such as nudibranchs (West et al., 1984; Sisson, 2002) and spionid polychaetes (Gibson and Gibson, 2004). In some cases different larval forms have been observed within the same population (Sisson, 2002). Such flexibility in population life histories of inner shelf benthos may be adaptive in an environment that is dynamic across multiple spatial and temporal scales.

A long-held assumption of larval life history traits is that planktotrophic forms evolved due to selective advantages of dispersal; however, pelagic larval stages may be adaptive primarily for entering a different trophic compartment, and dispersal may only be a by-product of that strategy (Giangrande et al., 1994). Species patterns in shallow shelf waters may in some cases be set by larval habitat selection and juvenile immigration from the local community (Snelgrove et al., 2001).

Osman and Whitlatch (1998) found that recruitment, abundance, and dominance within subtidal bryozoan and ascidian communities in southern New England persist year after year over large areas of the bottom, and they suggested that such persistence results from strong local control of recruitment that overrides any variability in larval production and dispersal of species from outside a site. Pelagic lecithotrophic larvae of some marine populations may be behaviorally constrained to minimize transport even in highly dispersive environments with strong tidal currents, resulting in spatial domination by a few, local species (Todd, 1998). Many of the abundant shoal-inhabiting taxa of the study area produce lecithotrophic larvae, including tunicates and nudibranchs. Gammarid amphipods, another common inhabitant of the shoals, are brooders without a larval stage (Barnes, 1980). Bivalves generally produce pelagic planktotrophic larvae. Surf clam eggs are planktotrophic, and fertilization occurs in the water column above beds of spawning clams (Ropes, 1980). The greatest concentrations of surf clams offshore the Delmarva Peninsula occur at depths of 18 to 36 m (Ropes, 1978), coinciding with depths near Weaver Shoal. Potential surf clam recruits may therefore originate locally. The evolution of local recruitment may be due to adaptive advantages of remaining in habitats suitable for population maintenance (Strathmann et al., 2002).

Decapod crustaceans are important community constituents in the offshore study area, though larvae may not originate in the immediate vicinity of the shoals. Adults of the abundant decapods of the study area occur along a continuum from estuaries to the open ocean, at varying abundance levels depending on season. Rock crabs (*Cancer* spp.) occur in estuaries and nearshore shelf locations primarily during colder months and move offshore during warmer months (Winget et al., 1974; Haefner and Van Engel, 1975; Haefner, 1976). Spider crabs (*Libinia* spp.) are most common in coastal waters during summer (Winget et al., 1974). Stehlik et al. (2004) found that lady crabs were most abundant in the Hudson-Raritan estuary between June and December.

Decapods often form mating aggregations, timed with female molting (Barnes, 1980). Inlets and other locations near areas of tidal flow may serve as aggregation sites for mating or as spawning sites for some decapods (Brookins and Epifanio, 1985; DeGoursey and Auster, 1992; Drake et al., 1998). Female blue crabs migrate from low salinity estuarine regions to high salinity regions near the mouths of estuaries prior to release of larvae (Carr et al., 2004; Aguilar et al., 2005). Stehlik et al. (2004) suggested that estuarine use by lady crabs may be related to reproduction, and Modlin (1962) found that female sevenspine bay shrimp migrated into a Connecticut estuary prior to larval release.

Proximity to estuarine inlets may promote entrainment of released decapod larvae by ebb tidal currents, transporting them to shelf waters where they develop. Larvae of blue crab, lady crab, rock crabs, sevenspine bay shrimp, and spider crabs develop through multiple zoeal stages in surface waters of the inner continental shelf. A post-larval stage (megalops) usually begins a benthic phase. Pelagic larvae of abundant decapods appear primarily during warmer months in the Mid-Atlantic Bight (Sandifer, 1973; Haefner, 1979; Dittel and Epifanio, 1982), though sevenspine bay shrimp larvae have been found to be abundant from late winter into spring (Sandifer, 1973; Wehrtmann, 1994). A pool of decapod larvae may exist seasonally in waters of the study area (Brookins and Epifanio, 1985), though larval cohorts tend to occur in discrete patches. Potential mechanisms for larval patch formation and maintenance include synchronous spawning events, associative larval behavior, and aggregative physical processes (Natunewicz and Epifanio, 2001).

Decapod larvae and post-larvae exhibit behavioral responses to physical environmental cues, resulting in dispersal patterns that may differ from patterns predicted based on large-scale hydrographic forces (Hines, 1986b). Crab larvae may regulate their vertical position in the water column in response to environmental cues or endogenous biological rhythms (DeVries et al., 1994; Forward et al., 1997; Garrison, 1999). Larvae may enter the water column on flood tides to be transported back into the estuary (Dittel and Epifanio, 1982), or remain on or near the bottom as a mechanism for retention in shelf waters (Epifanio, 1988; Zeng and Naylor, 1996). Epifanio (1988) found that lady crab larvae on the inner shelf remained nearer the substratum, whereas blue crab larvae, which return to estuaries during the megalops stage, remained close to the water surface. Individual behavior thus promotes retention of larval decapods in the vicinity of their parental populations, and this assures sufficient recruits for population maintenance (McConaugha, 1992).

The ability of fish populations to recolonize dredged shoals in the region is largely unexamined. Broad patterns may vary based on the degree of bottom-association, which can range from direct (e.g., flounder species living in the sediment) to highly indirect. In the latter case, species such as Atlantic mackerel or striped bass may associate with shoal features in transient manners associated with movements of schools (Able and Fahay, 1998). In transects north of the study shoals, 33 of 47 species collected included age-0 juveniles and 25 species were near settlement size (Steves et al., 1999). However, the scaling and habitat variability that can influence abundances is highly species-specific and can involve very different meso- and macro-scale drivers (Sullivan et al., 2000). Complex temporal variations in shoal use, including substantive diel variations, are driven in part by feeding cycles (Slacum et al., 2006). Recovery of fish populations will necessarily include the reestablishment of fundamental trophic functions.

4.5 SHOALS AS ESSENTIAL FISH HABITAT (EFH)

4.5.1 Management and Species Categories

Specific values of shoal habitats to Mid-Atlantic Bight fishes have been increasingly detailed in terms of both micro- and meso-scale habitat features (Diaz et al., 2003; Slacum et al., 2006; Vasslides and Able, 2008) with empirical reinforcement of EFH roles of offshore shoals. EFH is defined as “those waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity” [16 U.S.C. § 1801(10)]. The EFH final rule summarizing EFH regulations (50 CFR Part 600) outlines additional interpretation of the EFH definition. All eight Federal fishery management councils were mandated to amend management plans to identify EFH and anthropogenic threats by late1998. The Mid-Atlantic Fishery Management Council (MAFMC), with jurisdiction for Federal waters from Virginia to New York, identified EFH in amendments to the six fishery management plans that the council administers: spiny dogfish; Atlantic mackerel, squid, and butterfish; bluefish; summer flounder, scup, and black sea bass; surfclam and ocean quahog; and tilefish. Some of these species or other species that use shoals are also managed at the State and regional levels.

Table 4.7 summarizes the Federal, regional, and State managed fish species that can occur in association with the shoal features in the current study. Managed fish species include at least 15 bottom-associated species and at least 6 pelagic species that can associate with shoals. The bottom-associated fishes include flounders, rays, and sharks. Eight species, four demersal and four pelagic, had EFH designations within MAFMC jurisdiction. These shoals are also used by significant pelagic species such as the striped bass, which may use prominent bathymetric features such as our study sites for positioning and feeding during seasonal longshore migrations.

Table 4.7. Managed fish and invertebrate species that can utilize offshore sand shoals in the Mid-Atlantic Bight. Management agencies include: Mid-Atlantic Fishery Management Council (MAFMC); Atlantic States Marine Fishery Commission (ASMFC); several State fishery management agencies; National Marine Fisheries Service (NMFS), and New England Fishery Management Council (NEFMC). The Federal MAFMC and NMFS have primary fishery authority of the shoals in the present study. FMP Amd: Fishery Management Plan Amendment. HMS: Highly Migratory Species rules, NMFS.

Managed Fishes		MAFMC EFH Designation	ASFMC	Other
Scientific Name	Common Name			
Pelagic				
Morone saxatilis	Striped bass	None	Yes	
Pomatomus saltatrix	Bluefish	FMP Amd 1	Yes	
Scomber scombrus	Atlantic mackerel	FMP Amd 8	No	
Peprilus triacanthus	Butterfish	FMP Amd 8	No	
Stenotomus chrysops	Scup	FMP Amd 12	Yes	
Clupea harengus	Atlantic herring	No	Yes	
Demersal				
Paralichthys dentatus	Summer flounder	FMP Amd 12	Yes	
Centropristis striata	Black sea bass	FMP Amd 12	Yes	
Lophius americanus	Monkfish	No, NEFMC	No	
Scophthalmus aquosus	Windowpane flounder	None	No	NEFMC
Lopholatilus chamaeleonticeps	Tilefish	FMP Amd 1	No	
Squalus acanthias	Spiny dogfish	Original FMP	Yes	NEFMC
Micropogonias undulatus	Atlantic croaker	None	Yes	
Leiostomus xanthurus	Spot	None	Yes	
Pseudopleuronectes americanus	Winter flounder	None	Yes	NEFMC
Urophycis chuss	Red hake	None	No	NEFMC
Odontaspis taurus	Sand tiger shark	None	Yes	HMS
Cetorhinus maximus	Basking shark	None	Yes	HMS
Carcharhinus limbatus	Blacktip shark	None	Yes	HMS
Sphyrna lewini	Scalloped hammerhead	None	Yes	HMS
Carcharhinus signatus	Night shark	None	Yes	HMS
Carcharhinus brevipinna	Silky shark	None	Yes	HMS
Carcharhinus obscurus	Dusky shark	None	Yes	HMS
Carcharhinus plumbeus	Sandbar shark	None	Yes	HMS
Galeocerdo cuvieri	Tiger shark	None	Yes	HMS
Rhizoprionodon terraenovae	Atlantic sharpnose shark	None	Yes	HMS

Federally and state managed invertebrate species include three bottom-associated species and two pelagic species (**Table 4.8**). Both groups are under differing management and, potentially, very different invertebrate responses to sediment mining exist (e.g., quahog in comparision to squid).

Table 4.8. Managed invertebrate species that can utilize offshore sand shoals in the Mid-Atlantic Bight. Abbreviations provided in **Table 4.7**.

Managed Invertebrates		MAFMC EFH Designation	ASFMC	Other
Species Name	Common Name			
Pelagic				
Loligo pealei	Long-finned squid	FMP Amd 8	No	
Illix illecebrosus	Short-finned squid	FMP Amd 8	No	
Bottom-associated				
Spisula solidissima	Surfclam	FMP Amd 12	No	
Arctica islandica	Ocean quahog	FMP Amd 12	No	
Limulus polyphemus	Horseshoe crab	None	Yes	

Due to the breadth of the original EFH definition, the EFH guidelines also recognized subunits termed Habitat Areas of Particular Concern (HAPC) that could involve four criteria: (1) importance of ecological functions; (2) sensitivity to degradation; (3) probability and extent of effects from development; and (4) rarity. The MAFMC designated submerged aquatic vegetation (SAV) and macroalgae beds in nursery habitats as HAPC for juvenile and larval-stage summer flounder (MAFMC, 1998a). The Council did not identify HAPC for other species, concluding they did not have enough information to link habitat type with recruitment success (MAFMC, 1998b). The EFH Amendment notes the importance of these habitat types in providing summer flounder shelter from predators and prey, the first HAPC criterion. The MAFMC did not propose any special regulations for the areas designated as HAPC. The Amendment implies that the reason for this is that the majority of the designation is in state waters, where the Council does not have the authority to regulate fishing (Dobryzinski and Johnson, 2001).

4.5.2 Functional Values

The assessment of species and life stages associated with Mid-Atlantic Bight sand shoals in **Section 4.2** suggests that particular ecological functions of shoals can be evaluated. At broad spatial scales (1 to 100 km^2; macro), fishes may be using shoal features as guideposts during migrations, local movements, or spawning. At intermediate scales (10’s to 100’s m^2; meso), different parts of individual shoals may represent different foraging areas or shelter from predators or waves and currents. At smaller scales (e.g., cm^2 to m^2; micro), sediment texture (fine sand to shell fragments), variable bedform structures, and biogenic structures can be important as predator refuge or foraging areas. Considering this spatial framework, most fundamental ecological functions of shoals for fishes fall into the categories of spawning, shelter, or foraging.

4.5.2.1 Spawning

Spawning times and general locations are known for some Mid-Atlantic Bight species, and there are some general patterns that occur (Colton et al., 1979; Wilk et al., 1990). Evidence for spawning times comes from extensive egg and larval surveys and the examination of ovaries of mature adults (Colton et al., 1979; Wilk et al., 1990). Spatial and temporal distribution of eggs and early (pre-flexion) larvae are indicators of spawning. This has ramifications for the habitat function of shoals. One pattern of spawning by coastal fishes is to spawn in outer shelf waters often during winter months. Variations to this pattern are spawners that move offshore and south as far as Cape Hatteras to spawn (Cowen et al., 1993).

Other demersal species spawn in inner shelf waters without moving north or south. Wilk et al. (1990) followed ovarian development of 14 species including several known to be associated with shoals. Black sea bass, silver hake, red hake, butterfish, northern searobin, striped searobin (*Prionotus evolans*), and fourspot flounder (*Paralichthys oblongus*) spawn in summer months. Summer and winter flounder are offshore fall and winter spawners. Summer flounder spawning peaks in October and November as they migrate from estuaries to the OCS. This puts their spawning events into relatively close cross-shelf proximity to shoal systems. Exact locations of spawning relative to shoals are unknown for most fish species.

Precise spawning locations are not known from many species; however, based on the collection of early stage larvae, Able and Hagan (1995) and Able et al. (2006) showed that several taxa, including bay anchovy, spawn on the inner shelf in water depths similar to those of the focal shoals. However, species such as *Anchoa* also spawn inshore including euhaline estuarine areas. A clupeid and scombrid (bay anchovy and Atlantic mackerel) had the highest average numbers of eggs collected at Beach Haven Ridge, New Jersey, during the 1970's (Able and Hagan, 1995).

In contrast to inner and outer continental shelf spawners, anadromous species such as the striped bass spawn water-column eggs upstream in tributaries within estuaries of many major Mid-Atlantic Bight and New York Bight watersheds. In another life history variation, winter flounder spawn demersal eggs in estuaries. In the latter two species use of shoal habitats doesn't begin until at least one year and sometimes several years of estuarine maturation before consistent seasonal offshore migrations begin.

4.5.2.2 Shelter

The diversity of species of temperate shoal habitats and adjacent areas can be high, for example, 93 species from 47 families represented (Able and Hagan, 1995). Many demersal fishes of the region are characterized by complete age-class migrations across the shelf every approximate six months and associate with benthic habitats on a variety of spatial scales (Able and Fahay, 1998; Sullivan et al., 2000, 2006). At large scales (10's to 100's m^2), ridges and swales provide relief and habitat complexity, but for settling and juvenile fishes, structure at smaller scales (cm^2 to m^2) is more important (Diaz et al., 2003). Small-scale structure used by juvenile fishes as refuge from predation can be either physical (sand waves or bedforms) or biogenic (shell fragments, worm tubes, feeding pits, and other bioturbation) in nature.

Diaz et al. (2003) reported high fish densities associated with highest sand waves and concentrated worm tube aggregations on the inner continental shelf. Black sea bass juveniles prefer areas with accumulations of shells and shell fragments (Able et al., 1995). Auster et al. (1995) found young fishes on the outer shelf associated with a variety of small features such as sand waves, coarse material accumulated in the troughs of these waves, biogenic depressions (skate or ray feeding pits), clay outcrops, and boulders. It is likely that species utilizing shoals and surrounding areas would seek out similar microhabitats (Able et al., 1995; Diaz et al., 2003).

In areas where the seafloor is devoid of physical structure, both predators and prey must be able to burrow into the sediments for concealment. Several demersal species such as flatfishes (Paralichthyidae, Scophthalmidae, Pleuronectidae), searobins (*Prionotus* spp.), stargazers (Uranoscopidae), sand lances (Ammodytidae), and conger eels (Congridae) burrow or partially bury themselves in the sand. This phenomenon has not been formally studied, but such activity would require particular sediment size ranges and compaction characteristics; attributes that could be modified with excavation, particularly at erosional shoal areas. An additional but unstudied aspect of this behavior is that many species that burrow or are buried during the day emerge at night to forage under the guise of darkness (Auster et al., 1995).

Several of the demersal species that associate with shoals are known to also occur on artificial or naturally occurring hard bottom in the region (Eklund and Targett, 1991; Steimle and Zetlin, 2000). Most notable of these is the black sea bass, followed by red hake, conger eel (*Conger oceanicus*), and scup. This suggests that at least some of the demersal species have an affinity for high relief structure; perhaps shoals provide some element of this and serve as shelter or spawning sites. Habitat for pelagic species is generally determined by water column characteristics but can include artificial or natural structures. Habitat association may occur at a variety of spatial scales. Level sedimentary bottoms appear featureless at large scales; however, when viewed at finer scales, the details of bed form, bioturbation, sand waves, and sediment texture emerge as important for individuals of varying life stages. However, the role of shoals in transient movements, sometimes associated with seasonal cross-shelf migrations, is poorly known for most benthic and pelagic species.

Able et al. (2006) noted that several of the important Mid-Atlantic Bight fishes settled in both estuaries and coastal ocean waters. This distinction is important when interpreting the assumption of estuarine dependence in young fishes of many species. It appears that species settling in either estuaries or coastal oceans are growing and surviving at similar rates in the two habitats. Able et al. (2006) found only fourspine stickleback (*Apeltes quadracus*), naked goby (*Gobiosoma bosc*), and winter flounder (*Pseudopleuronectes americanus*) in estuarine waters. Nonresident species that settled exclusively in estuaries were tautog, dusky pipefish, weakfish, and cunner. Species settling in both estuarine and coastal ocean habitats included American sand lance (*Ammodytes americanus*), black seabass, seaboard goby, windowpane, red hake, Atlantic croaker (*Micropogonias undulatus*), smallmouth flounder, northern searobin, spotted hake, and stripped searobin.

There are special examples of symbiosis between juvenile red hake and the sea scallop *Placopecten magellanicus* (Steiner et al., 1982). Red hake reside within the mantle cavity of the scallop following settlement from a size of 30- to 116-mm standard length. Also, the inquiline snailfish (*Liparis inquilinus*) spends its entire adult life in a live sea scallop. Many demersal and pelagic species in the Mid-Atlantic Bight may use habitats in a facultative manner (e.g., similar-sized individuals may utilize different habitats at the same time) (Able et al., 2006). The pattern of settlement exhibited by these species was further supported from autecological studies on black sea bass (Able et al., 1995), windowpane (Morse and Able, 1995; Neuman and Able, 2002), and searobins (McBride et al., 1998). This latter group of species, particularly black sea bass and windowpane flounder, are relevant to the discussion of the importance of shoals as EFH in the region. Understanding the relative importance of different habitats to opportunistic species remains a continuous challenge for resource managers in tropical and temperate systems, as an absence of dependent usage doesn’t mean that a habitat may not have significant value (Lindeman et al., 2000; Able et al., 2006).

4.5.2.3 Foraging

Feeding habits of demersal fishes of the region have been summarized by recognizing that several dietary guilds exist (Garrison and Link, 2000). Dietary guilds are composed of species exploiting similar food resources on the open shelf. These guilds include crab eaters, planktivores, amphipod/shrimp eaters, shrimp/small fish eaters, benthivores, and piscivores (Garrison and Link, 2000; Link, 2002). The composition of particular feeding guilds depends upon morphological characteristics that change with growth of the fish. Thus, many species will change guild associations as they grow. Sissenwine (1984) characterized the northeast continental shelf ecosystem as predator-dominated. From the available information, it is conceivable that shoals provide either concentrations of invertebrates or more easily accessible prey due to the physical nature of the feature. This may be especially common in areas around the base of shoals.

The affinity of certain demersal fishes for particular sediment types often is related to the types of prey items supported by those sediments. Species such as skates, Atlantic croaker, spot, and winter flounder are bottom feeders that consume infaunal and epibenthic crustaceans and polychaetes. Amphipods are known to be important in the diets of some demersal fishes, including cod, haddock, and winter flounder. Certain demersal foragers may therefore be attracted to areas of medium to coarse sands, where crustaceans and polychaetes are most abundant (Wigley and Theroux, 1998).

Pelagic groups of shoal-associated fishes may be divided into large bodied piscivores and smaller bodied planktivores. Forage species are attracted to shoals or other high relief features because of hydrodynamics and their effects on the prey capture. Piscivores include Spanish mackerel, bluefish, striped bass, and sharks. These species comprise the predatory component, whereas the smaller planktivores such as anchovies, Atlantic menhaden, herrings, alewives, and shad form the prey component of the pelagic assemblage. This connection between predatory species and their prey has been well documented for striped bass (Overton et al., 2007). Many of the piscviorous predators such as bluefish and striped bass are attracted to concentrations of clupeoid prey (herrings and anchovies) that may form in association with shoals. Overton et al. (2007) documented that coastal populations of striped bass fed primarily on bay anchovy and Atlantic menhaden—two species regularly collected around shoals of the region. Shoals may also affect circulation patterns in such a way that planktonic prey are more readily obtained by water column foragers.

4.6 SHOAL HABITATS IN COMPARISON TO OTHER CROSS-SHELF FEATURES

Many geomorphological features of offshore shoals can promote increased, localized biological productivity. Fish usage of the habitats within many physiographic gradients across the shelf was characterized to examine the comparative roles of spatially distinct cross-shelf macrohabitat features, and temporal variability of their use. These features are influenced by inshore estuarine habitats and inlet passages to the ocean, in addition to the raised bathymetric profiles that shoal systems such as Weaver/Isle of Wight present to any organisms that annually transit the shelf as part of their life history (Able and Fahay, 1998; Maa et al., 2004).

The assessment of species distributions across an entire shelf, and on the finer scale of structural bottom types, is limited by the absence of empirical data, and also larger spatial frameworks that incorporate both small-scale structural and large-scale physiographic attributes within a cross-shelf continuum. Such a framework should explicitly characterize several spatial scales across heterogeneous seascapes, reflect temporally variable ontogenetic migrations and be of use to administrators charged with decision-making in areas with varying levels of baseline data.

4.6.1 Characterizing Cross-shelf Gradients and Habitats

A spatial framework for assessing habitat use was developed following the above goals. The specific objectives in developing this cross-shelf habitat (CSH) framework were to (1) define spatial scales for structural bottom-types and their physiographic backdrops (cross-shelf strata); (2) integrate these features using a matrix that combines a structural axis and a physiographic axis in a geographically logical manner; and (3) apply CSH matrices of habitats within strata to examine distributions and coarse relative abundance patterns among the primary habitats of the heterogeneous seascape under study (Lindeman et al., 1998; Ault et al., 1999).

Two spatial scales were emphasized: structural habitats and cross-shelf strata. Habitats were defined as structural bottom-types on spatial scales of 0.1 to 1 m^3 that provide shelter or trophic resources. Twelve natural habitat types, noninclusive for all of the structural combinations present, were used based on the literature for the region and assigned mnemonic acronyms (**Table 4.9**). Ten cross-shelf strata, were postulated to extend from inshore mainland areas to the outer shelf east of the study area. These strata were based on (1) bathymetry; and

(2) cross-shelf positioning relative to emergent sedimentary barrier islands and submerged shoals.

Table 4.9. Structural habitat types occupying volumes of 1 m^3.

Habitat Category	Habitat Type
Sediment	Fine sediments
	Coarse sediments
	Shell
Invertebrate Structure	*Diopatra* tubes
	Asabellides
	Other
Submerged Aquatic Vegetation	*Zostera*
	Macroalgae
	Combination
Emergent Vegetation	*Spartina alterniflora*
	Juncus
	Phragmites

From inshore to offshore, the cross-shelf strata used were: Mainland Shore, 0 to 2 m; Basin Axis, >2 m (e.g., Isle of Wight Bay); Leeward Shore, 0 to 2 m; Inlet Axis, >2 m (e.g., Ocean City Inlet); Inshore Shallow, <4 m; Inshore Deep, 4 to 15 m; Mid-shelf Shallow; Leading Edge of Shoal; Trailing Edge of Shoal; Mid-shelf Deep. For both habitats and cross-shelf strata, the specific named categories are nominal: future iterative revision is encouraged.

Intersections of individual habitat types and cross-shelf strata form cells or cross-shelf habitats within the matrix. For example, one cross-shelf habitat is fine sediment within the axis of a channel in a barrier island inlet (IA). At least 116 cross-shelf habitats were nominally identified. Cross-shelf habitat attributes of offshore shoals were emphasized as a heuristic aid to questions in **Section 6** on dredge alternatives for different shoal areas. Physiographic gradients associated with shoals are influenced by depositonal patterns and can include leading edge of shoal, trailing edge of shoal, and trough, flank, and crest subareas.

Four of the cross-shelf strata were within estuarine areas inside ocean inlets (e.g., Isle of Wight Bay and Ocean City Inlet). Six others extended from oceanic channels of the barrier islands to the outer shelf edge. These strata are proxies for gradients of other physical variables often correrelated with depth and cross-shelf position (e.g., salinity, turbidity, and wind exposure) that can distribute in semi-continuous bands across the shelf. Since fish usage of similar structural habitats may vary along physically different sections of shelves, cross-shelf strata can represent bio-physical gradients following Keddy (1991), who suggested that environmental gradients are useful but often underused research tools.

4.6.2 Cross-shelf Patterns of Habitat Use Among Some Demersal and Pelagic Species

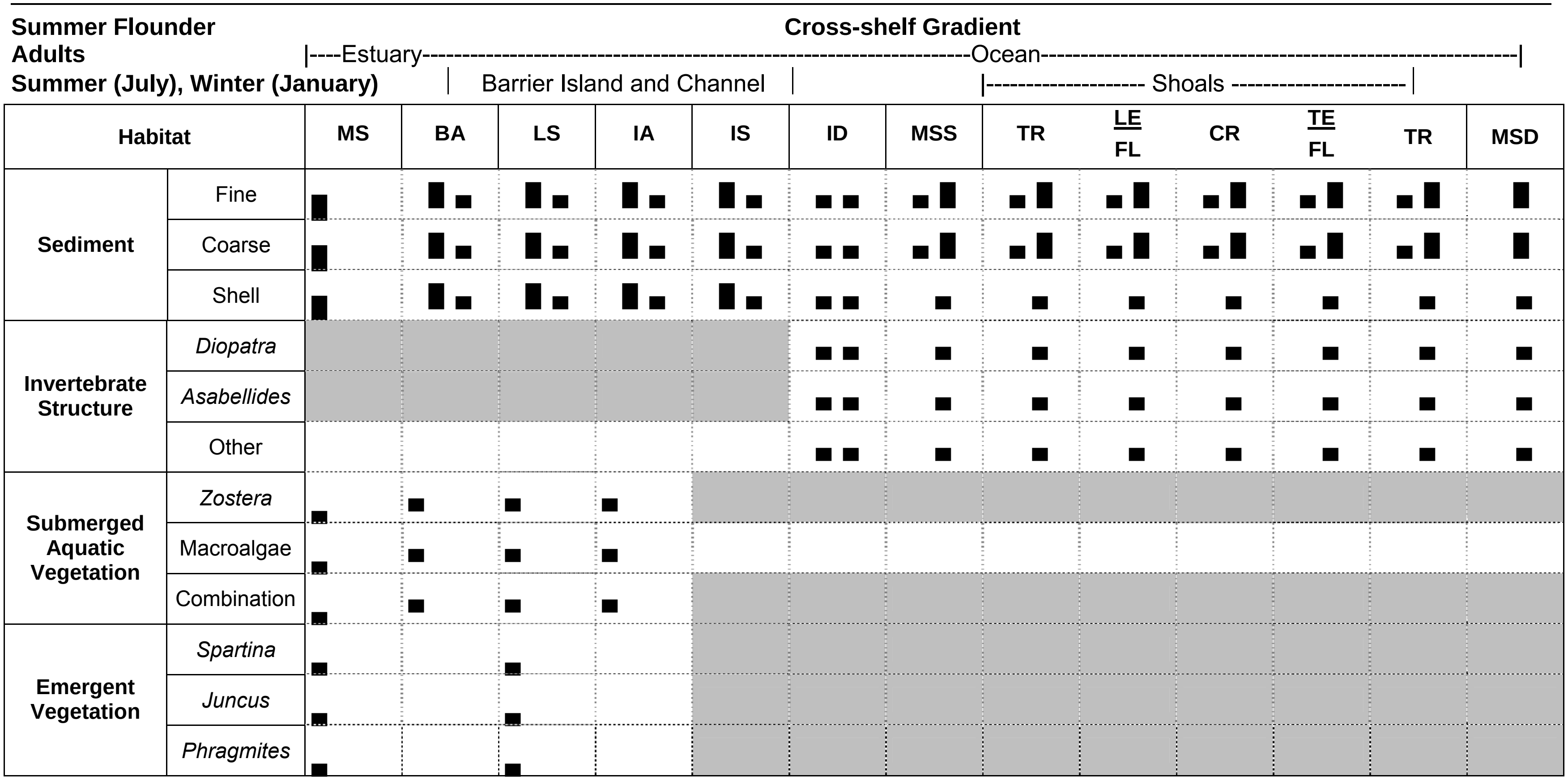
A CSH matrix of primary habitat combinations from the OCS into the northern Delaware estuaries was generated by superimposing structural habitats on a vertical axis and cross-shelf strata on a horizontal axis. Four fish species representative of differing life history strategies and benthic and pelagic water column positioning were used to populate cross-shelf habitat matrices by seasons and key life stages. The species represented several significant life history patterns, economic interests, and trophic drivers and included summer flounder and windowpane, abundant flatfishes that undergo substantial cross-shelf migrations and are harvested significantly. Also examined were bay anchovy, an abundant and widely distributed baitfish and prey item, and striped bass, an anadromous gamefish that can distribute widely across the shelf.

The literature used to estimate cross-shelf distributional patterns and coarse relative abundances across estuarine to OCS cross-shelf gradients included reviews (Able and Fahay, 1998; VIMS, 2000; Able et al., 2007), empirical studies for the project area (e.g., Diaz et al., 2003; Slacum et al., 2006), and empirical studies from the shoal study area off New Jersey, Beach Haven Ridge (e.g., Able and Hagan, 1995; Able et al., 2006). Combinations of cross-shelf habitats that are used abundantly can be termed habitat mosaics. Several combinations of spatial scales were examined depending on the organisms, life stages, and processes of interest to expose habitat mosaics of interest in terms of bio-physical dredging issues or data needs.

The summer flounder is an example of an economically important sediment-dwelling species that engages in substantial cross-shelf migrations repeatedly through its life cycle (Able et al., 1990; Able and Kaiser, 1994). For some of the summer flounder subpopulations within this range of the Mid-Atlantic Bight, these migrations probably involve the shoals in the present study (Diaz et al., 2003). **Figures 4.3** and **4.4** show the estimated summer and winter array of cross-shelf habitats used by the summer flounder, with relative abundances for summer and winter, July and January, respectively. Evidence suggests that almost all adults are out of the region's estuaries by November or December (Able and Fahay, 1998). Use of the study shoals is particularly likely for cross-shelf migrators that emigrate out of Ocean City Inlet.

Some of the most prominent patterns of cross-shelf habitat use for summer flounder include the absence of settlement in ocean environments and the biannual, long cross-shelf migration juveniles and adults make from estuaries to overwinter offshore. As seen in **Figure 4.3**, these migration events potentially place juvenile and adult life stages of summer flounder into multiple combinations of habitats within diverse cross-shelf gradients. Almost all of the cross-shelf strata between estuaries and the deeper shelf (>100 cross-shelf habitat cells), including the project shoals, are potentially bidirectionally transited by the same individual fishes on two long migrations per year (**Figure 4.3**), perhaps using very similar paths that ultimately traverse several tens of kilometers. The decision making by these fishes requires further investigation, perhaps by modeling of habitat selection decisions.

The windowpane flounder is an important flatfish that differs from summer flounder in cross-shelf habitat usage in some attributes. At the broadest scale, it is not an estuarine-only settler, instead settling in both estuarine and ocean environments (Morse and Able, 1995; Able et al., 2006). **Figure 4.4** shows relative abundance estimates among cross-shelf strata and habitats within. Neuman and Able (1998) found that windowpane of all sizes preferred sand over mud, but there were differences in sediment preference, burial behavior, and pigment between transitional larval and juvenile stages. Numbers of juveniles can be substantially higher in ocean areas, though juveniles can occur abundantly in estuaries. The patterns are complicated, for example, Neuman et al. (2001) and Neuman and Able (2002) found that growth and settlement patterns varied with season of spawning. Evidence suggests that spring-spawned age classes occurred in both ocean and estuary areas, whereas fall-spawned cohorts settled predominantly in the ocean (Morse and Able, 1995).



Summer Flounder **Cross-shelf Gradient**
Adults |----Estuary--Ocean---|
Summer (July), Winter (January) | Barrier Island and Channel | |------------------- Shoals ---------------------|

Habitat		**MS**	**BA**	**LS**	**IA**	**IS**	**ID**	**MSS**	**TR**	**LE** **FL**	**CR**	**TE** **FL**	**TR**	**MSD**
Sediment	Fine	▮	▮ ▪	▮ ▪	▮ ▪	▮ ▪	▪ ▪	▪ ▮	▪ ▮	▪ ▮	▪ ▮	▪ ▮	▪ ▮	▮
	Coarse	▮	▮ ▪	▮ ▪	▮ ▪	▮ ▪	▪ ▪	▪ ▮	▪ ▮	▪ ▮	▪ ▮	▪ ▮	▪ ▮	▮
	Shell	▮	▮ ▪	▮ ▪	▮ ▪	▮ ▪	▪ ▪	▪	▪	▪	▪	▪	▪	▪
Invertebrate Structure	*Diopatra*	▨	▨	▨	▨	▨	▪ ▪	▪	▪	▪	▪	▪	▪	▪
	Asabellides	▨	▨	▨	▨	▨	▪ ▪	▪	▪	▪	▪	▪	▪	▪
	Other						▪ ▪	▪	▪	▪	▪	▪	▪	▪
Submerged Aquatic Vegetation	*Zostera*	▪	▪	▪	▪	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Macroalgae	▪	▪	▪	▪									
	Combination	▪	▪	▪	▪	▨	▨	▨	▨	▨	▨	▨	▨	▨
Emergent Vegetation	*Spartina*	▪		▪		▨	▨	▨	▨	▨	▨	▨	▨	▨
	Juncus	▪		▪		▨	▨	▨	▨	▨	▨	▨	▨	▨
	Phragmites	▪		▪		▨	▨	▨	▨	▨	▨	▨	▨	▨

Gradients associated with shoals: LE = leading edge; TE = trailing edge. Shoal subareas: TR = trough; FL = flank; CR = crest. Physical attributes of cross-shelf gradients cited in text: MS = Mainland Shore; BA = Basin Axis; LS = Leeward Shore; IA = Inlet Axis; IS = Inshore Shallow; ID = Inshore Deep; MSS = Mid-shelf Shallow; MSD = Mid-shelf Deep.

Figure 4.3. Estimates of summer flounder (*Paralichthys dentatus*) cross-shelf distribution and relative abundance ranks of adults during summer and winter, stratified according to habitat and physical cross-shelf gradient. Solid bars represent abundance ranks based on high, low, and rare or no occurrence derived from literature cited in text. Shaded cells reflect habitats that do not occur within certain cross-shelf gradients.

Windowpane Flounder
Larvae and Early Juveniles
Summer (July), Winter (January)

Cross-shelf Gradient

|----Estuary--Ocean----------------------------------|

| Barrier Island and Channel |

|--------------------- Shoals ---------------------|

Habitat		**MS**	**BA**	**LS**	**IA**	**IS**	**ID**	**MSS**	**TR**	**LE** **FL**	**CR**	**TE** **FL**	**TR**	**MSD**
Sediment	Fine	▁	■	■	■	■ █	■ █	█	█	█	█	█	█	█
	Coarse	▁	■	■	■	■ █	■ █	█	█	█	█	█	█	█
	Shell	▁	■	■	■	■ █	■ █	■	■	■	■	■	■	■
Invertebrate Structure	*Diopatra*	▨	▨	▨	▨	▨		■	■	■	■	■	■	■
	Asabellides	▨	▨	▨	▨	▨		■	■	■	■	■	■	■
	Other													
Submerged Aquatic Vegetation	*Zostera*	▁	■	■	■	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Macroalgae	▁	■	■	■									
	Combination	▁	■	■	■	▨	▨	▨	▨	▨	▨	▨	▨	▨
Emergent Vegetation	*Spartina*	▁	■	▁		▨	▨	▨	▨	▨	▨	▨	▨	▨
	Juncus	▁	■	▁		▨	▨	▨	▨	▨	▨	▨	▨	▨
	Phragmites	▁	■	▁		▨	▨	▨	▨	▨	▨	▨	▨	▨

Gradients associated with shoals: LE = leading edge; TE = trailing edge. Shoal subareas: TR = trough; FL = flank; CR = crest. Physical attributes of cross-shelf gradients cited in text: MS = Mainland Shore; BA = Basin Axis; LS = Leeward Shore; IA = Inlet Axis; IS = Inshore Shallow; ID = Inshore Deep; MSS = Mid-shelf Shallow; MSD = Mid-shelf Deep.

Figure 4.4. Estimates of windowpane flounder (*Scophthalmus aquosus*) cross-shelf distribution and relative abundance ranks of larvae and early stage juveniles during summer and winter, stratified according to habitat and physical cross-shelf gradient. Solid bars represent abundance ranks based on high, low, and rare or no occurrence derived from literature cited in text. Shaded cells reflect habitats that do not occur within certain cross-shelf gradients.

The bay anchovy is by many measures, one of the most important fishes of both estuaries and the inner continental shelf of the Mid-Atlantic Bight. Its distribution is ubiquitous compared to many species (Martino and Able, 2003) both in terms of cross-shelf strata and habitats (**Figure 4.5**), and can have less direct structural habitat associations than many species. In various studies, bay anchovy abundances surpass most or all other species of fishes (Able and Fahay, 1998; Martino and Able, 2003). The widespread distribution is most manifest in summer months when the species occurs abundantly in diverse water column habitats from estuarine tributaries to the inner continental shelf, including the area of the project shoals (Slacum et al., 2006).

The striped bass spawns in freshwater tributaries yet adults can occur thoughout the inner continental shelf. Like many pelagic fish species, striped bass undergo substantial seasonal migrations (Able et al., 2006). These migration events place striped bass into multiple combinations of habitats within diverse cross-shelf gradients on and between migrations in adult stages (**Figure 4.6**). Larvae and juveniles, however, are much more seasonally restricted to estuarine areas where they can show complex patterns of space use (Able and Grothues, 2007), rarely occurring offshore in the winter (Able and Fahay, 1998). The migratory “paths” that flatfishes follow may be very specific to certain near-bottom habitat attributes. In contrast, for fast pelagic fishes like striped bass, high in the water column, offshore sand shoals may have somewhat differing roles in these migrations. For either life history pattern, prominent shoals could have functions as navigational bearings for long transits across the shelf, elevated energetic production as concentrated feeding areas, or other important life history functions (potential near-spawning areas for summer flounder).

4.6.3 Cross-shelf Distributional Patterns of Demersal and Pelagic Species

Several differing coastal fish assemblages of the Mid-Atlantic Bight and southern New York bight regions have been identified in prior studies. Steves et al. (1999) identified three cross-shelf zones with relatively distinct fishes (inner, middle, and outer) correlated in part with summer hydrographic fronts. Three species assemblages (inshore, near-ridge, and offshore) were identified by Vasslides and Able, 2008. The inner shelf fish species typically settle in estuaries or the ocean, or estuaries only, not in the ocean only (Able et al., 2006). Importantly, the majority of species that settle in both estuary and ocean settle more abundantly in ocean than estuarine areas. Many prominent fishes are driven to major, cross-shelf migrations every 6 months by seasonal temperature changes, including many harvested drums and croakers (sciaenids), in addition to benthic flatfishes and coastal pelagics. The potential for high specificity in habitat use exists, but may also be masked somewhat by the frequent movements and underlying opportunism implied by such wide, estuarine to oceanic cross-shelf distributions.

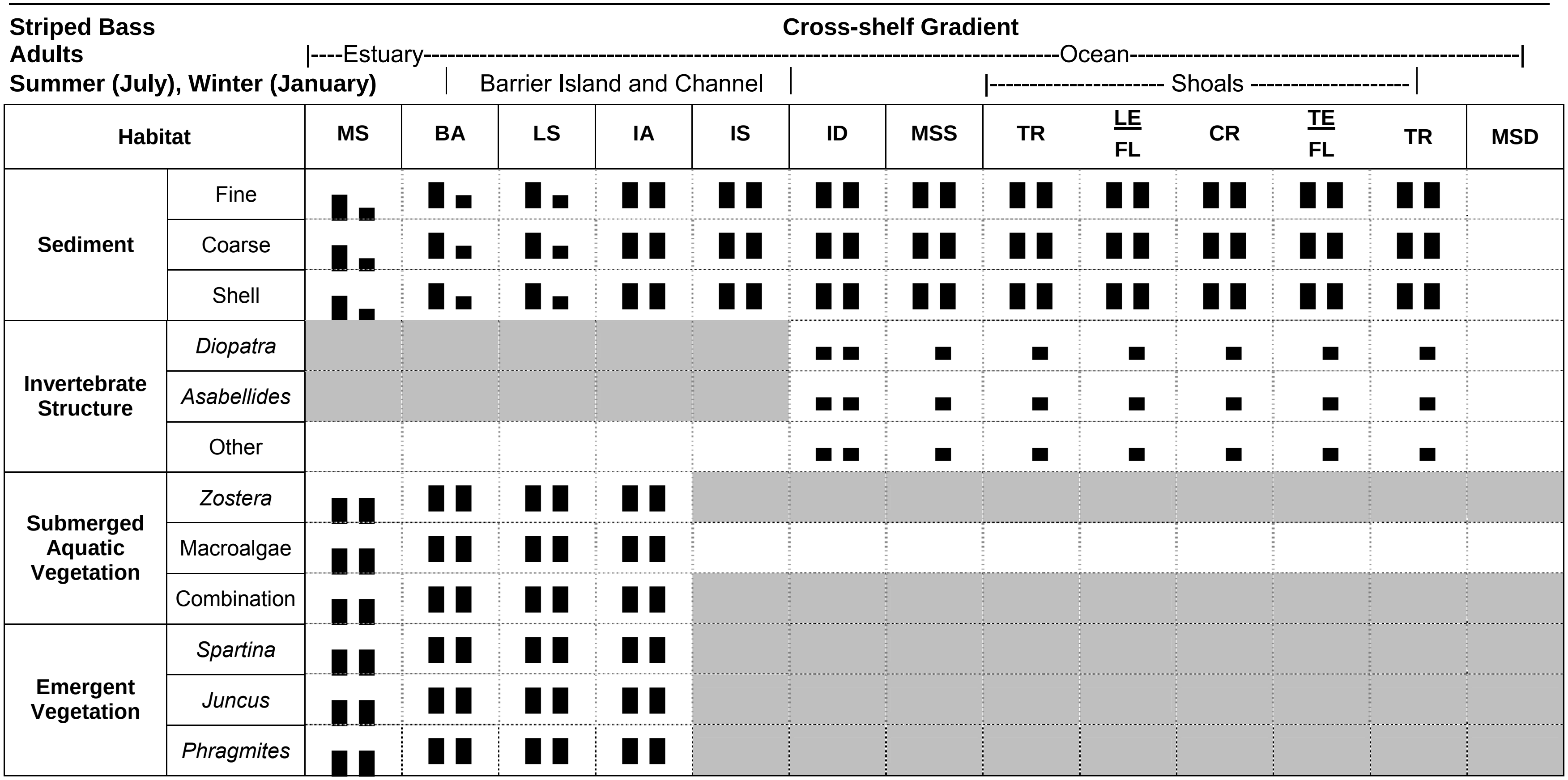
Among shoals of southern New Jersey, fish species richness was higher at near-ridge stations, especially in the fall during overwintering of many species (Vasslides and Able, 2008). Fall is the one season when bay anchovy are not abundant on the shoals, as this is an inshore spawning period. However, many other species are present in the fall (**Figures 4.3** to **4.6**). At various smaller habitat and microhabitat scales, there are a variety of drivers of observed diversity and abundance of fishes and invertebrates, including the length and height of bedforms and the density of biogenic structures (Diaz et al., 2003, 2004), fine-scale features that are difficult to measure at fine temporal or spatial scales. Probable diel differences include dispersal of various motile invertebrates away from dense biogenic structures (such as *Diopatra* tube mats) at night. Slacum et al. (2006) found diel differences in pelagic fish abundances, but mechanisms are unknown.

Bay Anchovy **Cross-shelf Gradient**
Larvae and Early Juvenile |----Estuary---Ocean---|
Summer (July), Winter (January) | Barrier Island and Channel | |----------------------- Shoals -------------------------|

Habitat		**MS**	**BA**	**LS**	**IA**	**IS**	**ID**	**MSS**	**TR**	**LE** **FL**	**CR**	**CR**	**TE** **FL**	**TR**	**MSD**
Sediment	Fine	▮ ▮	▮ ▪	▮ ▮	▮	▮		▮	▮	▮	▮	▮	▮	▮	
	Coarse	▮ ▮	▮ ▪	▮ ▮	▮	▮		▮	▮	▮	▮	▮	▮	▮	
	Shell	▮ ▮	▮ ▪	▮ ▮	▮	▮		▮	▮	▮	▮	▮	▮	▮	
Invertebrate Structure	*Diopatra*	░	░	░	░	░		▮	▮	▮	▮	▮	▮	▮	
	Asabellides	░	░	░	░	░		▮	▮	▮	▮	▮	▮	▮	
	Other							▮	▮	▮	▮	▮	▮	▮	
Submerged Aquatic Vegetation	*Zostera*	▮ ▮	▮ ▪	▮ ▮	▮	░	░	░	░	░	░	░	░	░	░
	Macroalgae	▮ ▮	▮ ▪	▮ ▮	▮										
	Combination	▮ ▮	▮ ▪	▮ ▮	▮	░	░	░	░	░	░	░	░	░	░
Emergent Vegetation	*Spartina*	▮ ▮	▮ ▪	▮ ▮	▮	░	░	░	░	░	░	░	░	░	░
	Juncus	▮ ▮	▮ ▪	▮ ▮	▮	░	░	░	░	░	░	░	░	░	░
	Phragmites	▮ ▮	▮ ▪	▮ ▮	▮	░	░	░	░	░	░	░	░	░	░

Gradients associated with shoals: LE = leading edge; TE = trailing edge. Shoal subareas: TR = trough; FL = flank; CR = crest. Physical attributes of cross-shelf gradients cited in text: MS = Mainland Shore; BA = Basin Axis; LS = Leeward Shore; IA = Inlet Axis; IS = Inshore Shallow; ID = Inshore Deep; MSS = Mid-shelf Shallow; MSD = Mid-shelf Deep.

Figure 4.5. Estimates of bay anchovy (*Anchoa mitchilli*) cross-shelf distribution and relative abundance ranks of larvae and early stage juveniles during summer and winter, stratified according to habitat and physical cross-shelf gradient. Solid bars represent abundance ranks based on high, low, and rare or no occurrence derived from literature cited in text. Shaded cells reflect habitats that do not occur within certain cross-shelf gradients.



Striped Bass
Adults
Summer (July), Winter (January)

Cross-shelf Gradient
|----Estuary--Ocean--|
| Barrier Island and Channel |
|-------------------- Shoals -------------------|

Habitat		**MS**	**BA**	**LS**	**IA**	**IS**	**ID**	**MSS**	**TR**	**LE** **FL**	**CR**	**TE** **FL**	**TR**	**MSD**
Sediment	Fine	▮▪	▮▪	▮▪	▮▮	▮▮	▮▮	▮▮	▮▮	▮▮	▮▮	▮▮	▮▮	
	Coarse	▮▪	▮▪	▮▪	▮▮	▮▮	▮▮	▮▮	▮▮	▮▮	▮▮	▮▮	▮▮	
	Shell	▮▪	▮▪	▮▪	▮▮	▮▮	▮▮	▮▮	▮▮	▮▮	▮▮	▮▮	▮▮	
Invertebrate Structure	*Diopatra*	▨	▨	▨	▨	▨	▪▪	▪	▪	▪	▪	▪	▪	
	Asabellides	▨	▨	▨	▨	▨	▪▪	▪	▪	▪	▪	▪	▪	
	Other						▪▪	▪	▪	▪	▪	▪	▪	
Submerged Aquatic Vegetation	*Zostera*	▮▮	▮▮	▮▮	▮▮	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Macroalgae	▮▮	▮▮	▮▮	▮▮									
	Combination	▮▮	▮▮	▮▮	▮▮	▨	▨	▨	▨	▨	▨	▨	▨	▨
Emergent Vegetation	*Spartina*	▮▮	▮▮	▮▮	▮▮	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Juncus	▮▮	▮▮	▮▮	▮▮	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Phragmites	▮▮	▮▮	▮▮	▮▮	▨	▨	▨	▨	▨	▨	▨	▨	▨

Gradients associated with shoals: LE = leading edge; TE = trailing edge. Shoal subareas: TR = trough; FL = flank; CR = crest. Physical attributes of cross-shelf gradients cited in text: MS = Mainland Shore; BA = Basin Axis; LS = Leeward Shore; IA = Inlet Axis; IS = Inshore Shallow; ID = Inshore Deep; MSS = Mid-shelf Shallow; MSD = Mid-shelf Deep.

Figure 4.6. Estimates of striped bass (*Morone saxatilis*) cross-shelf distribution and relative abundance ranks of adults during summer and winter, stratified according to habitat and physical cross-shelf gradient. Solid bars represent abundance ranks based on high, low, and rare or no occurrence derived from literature cited in text. Shaded cells reflect habitats that do not occur within certain cross-shelf gradients.

In all cross-shelf habitat matrices (**Figures 4.3** to **4.6**), the cross-shelf gradient axis included trailing edge and leading edge strata with trough, flank, and crest habitats imbedded within. However, intra-shoal variations in relative abundances of the species examined do not differ within seasons. This is a function of limited data. There are some generic management assumptions regarding the relative productivity of flanks, troughs, and crests. For example, an NMFS EFH Stipulation from the Sandbridge, Virginia, lease, issued by MMS, states that “To the maximum extent possible, the dredging contractor remove surficial sediment from shoal flanks compared to shoal crests and adjacent troughs, areas that are generally more biologically productive.” The relative degree of site specificity for such conclusions can be very high, subject to high temporal variation, and high species-specific differences in habitat use.

Troughs had the highest summer flounder numbers in the study area (Slacum et al., 2006). In the Maryland-Delaware shoals study by VIMS (2000) flanks and crests both yielded fewer species and less biomass than troughs. Some bivalves were more common along the crests (VIMS, 2000), and since bivalves are important contributors to secondary production, there potentially could be elevated impacts with the relative amount of biomass removed on a crest compared to a dredge site on a flank. Compared to abundance and diversity indices, biomass sometimes does take longer to recover in dredged sites (Newell et al., 1998). But larger, more mature bivalves generally are less commonly consumed by motile epifauna, such as sea stars and crabs, because of shell thickness. Loss of trophic function with the removal of sediments is a temporary consequence of dredging. Until recolonization occurs, motile foragers would feed in nearby nondredged areas. It isn't entirely clear that dredging a crest site results in greater impairment of ecological function compared to a flank site. And not all flanks are the same (**Section 4.2**), as there are differences in community patterns between the current-facing and lee sides of some shoals.

In summary, data gathered from individual shoals confirmed that a diverse assemblage of demersal and pelagic fishes associate with regional sand shoals and potentially use these shoals for feeding, spawning, and growing to maturity. Benthic invertebrates that contribute structural fish habitat (worm tubes, burrows, and bioturbation) as well as a forage base for demersal feeders also associate with sand shoals. Field studies of adult fish species collected by trawl and gill nets confirm that benthic feeders such as skates, scup, drums, searobins, flounders, and black sea bass occur around shoals and adjacent sand bottom areas. These species are behaviorally and morphologically adapted for bottom feeding in sedimentary environments. Pelagic species such as bay anchovy, Atlantic menhaden, Atlantic mackerel, butterfish, and striped bass were also documented to associate with shoals. It is possible that hydrodynamic effects of the shoal features aid in water column feeding by these species. Spawning by fishes in the vicinity of sand shoals can be inferred from the presence of eggs and early stage larvae. Plankton net samples revealed that anchovy, Atlantic menhaden, Atlantic mackerel, and searobins spawn in the vicinity of shoals in the Mid-Atlantic Bight. Shoals may also be important as juvenile habitat for species that utilize both inshore estuarine habitats and the nearshore shelf as nursery areas. The obligate nature of the association by demersal or pelagic fishes with shoals is not known, but it appears that many species rely on shoal features as a part of a broader, cross-shelf habitat continuum within which to complete their life cycles. Thus, based on the information gathered, sand shoals can certainly be considered EFH and efforts should be made to avoid or minimize any adverse effects produced by sand dredging.

5.0 SELECTION OF ALTERNATIVE SCENARIOS AND SIMULATION OF PHYSICAL PROCESSES

(Mark R. Byrnes – Applied Coastal Research and Engineering, Inc.)

5.1 PHYSICAL CONSIDERATIONS

Shoal and intershoal regions on continental shelves are predominantly composed of fine to coarse, well-sorted sand that is highly variable in thickness and areal extent. As shoals migrate and sand is reworked, coarse sediment becomes concentrated in areas of greatest wave and current energies, typically located along the crests of shoals. Shoal crests often contain very little shell material (Swift and Field, 1981; Snedden et al., 1999). Shoal flanks are composed of sand and some shell and biogenic material. Intershoal sands contain the most biogenic material, but it is never abundant. Wave and current energies prevent mud from being deposited in the area. Existing mud and fine sand from underlying deposits are often locally exposed on the seafloor. Sand deposits in these areas are usually only a few meters thick and have an overall grain size smaller than that of shoals and mainland beaches.

5.1.1 Specific Shoal Characteristics

Ocean City is one of the most popular seaside resorts on the east coast. Currently, Fenwick Island beaches are part of an engineered system. Regardless of the accumulation of sand on the updrift side of the north jetty, frequent beach nourishment is needed to maintain a beach along Fenwick Island. Regular sand placement on the beach provides protection against storms and preserves the recreational beach. The most recent investigation of borrow sources was carried out by USACE (2008). Their findings identify three large candidate shoals 14 to 18 km offshore of Ocean City as potential sand resources for the maintenance of existing beach conditions. This present report evaluates several scenarios for sand removal from shoals, as well as possible impacts to each shoal from the different dredging procedures.

Offshore shoals of particular interest include Weaver, Isle of Wight, and Shoal A (**Figure 5.1**). These three shoals were selected based on several criteria, such as sand quality and volume and proximity to the Ocean City beach. These criteria are discussed completely in USACE (2008). Other shoals were rejected from consideration for a variety of reasons such as poor sand quality, greater distance from the shore, recent dredging activities, existing fish habitats, and use in commercial and recreational fishing. Potential borrow sites were evaluated by obtaining sand samples collected from vibracores and grab samples. Patterns of sand source suitability from these analyses are displayed in **Figures 5.2**, **5.3**, and **5.4**. Borrow site maps were created by USACE and superimposed on the 2002 bathymetry surface. Ideally, sand source grain size should be similar to that of beach sand currently present at the site of beach nourishment. Prior to regular beach nourishment that began in 1988, Ocean City beach sand had a mean grain size of 0.6 mm (USACE, 1989). After several beach fills using offshore sand, mean grain size in 1993 was 0.43 mm (USACE, 2008).

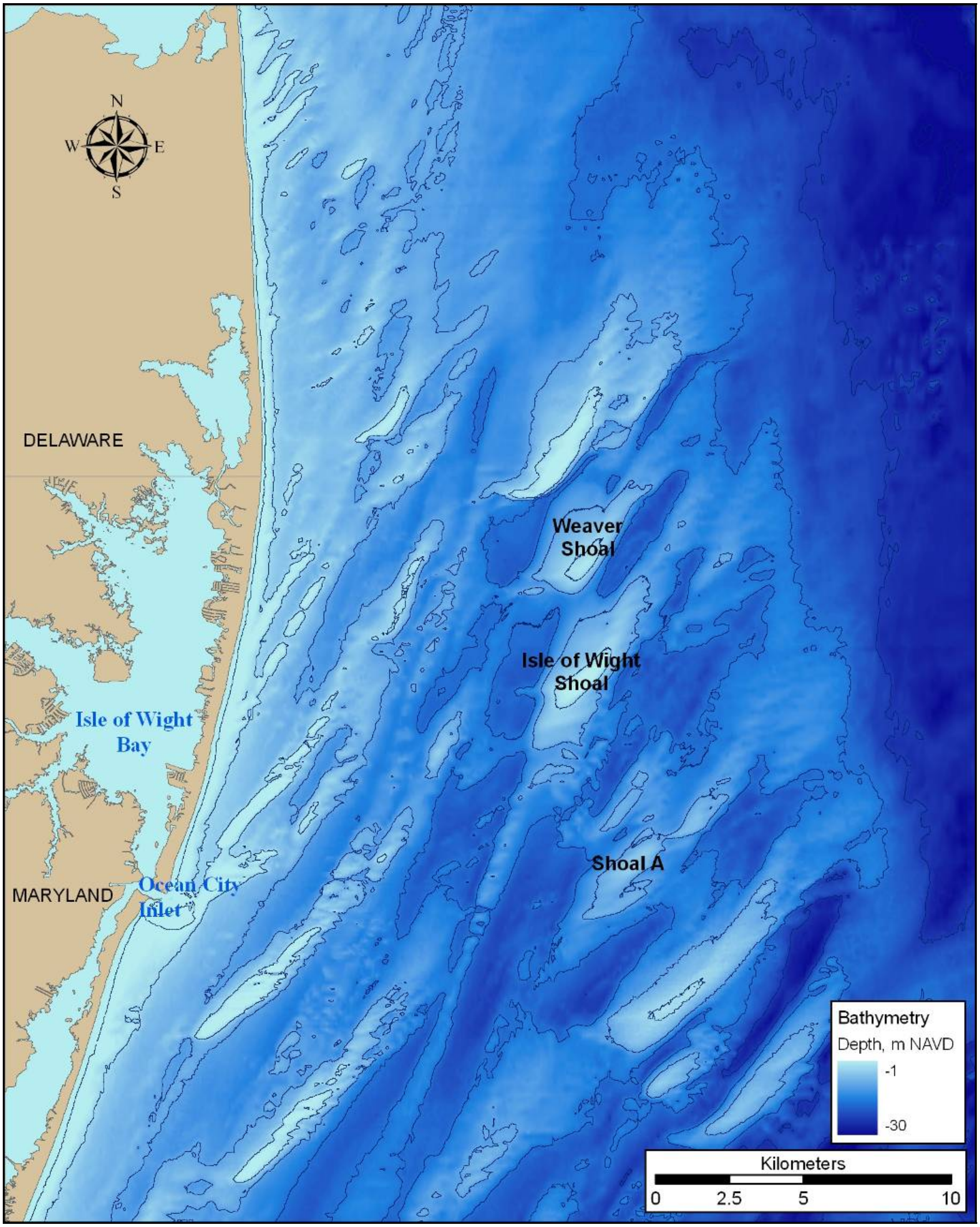


Figure 5.1. Bathymetric map of the study area documenting three offshore shoals evaluated for potential sand mining for Ocean City, Md., beach nourishment.

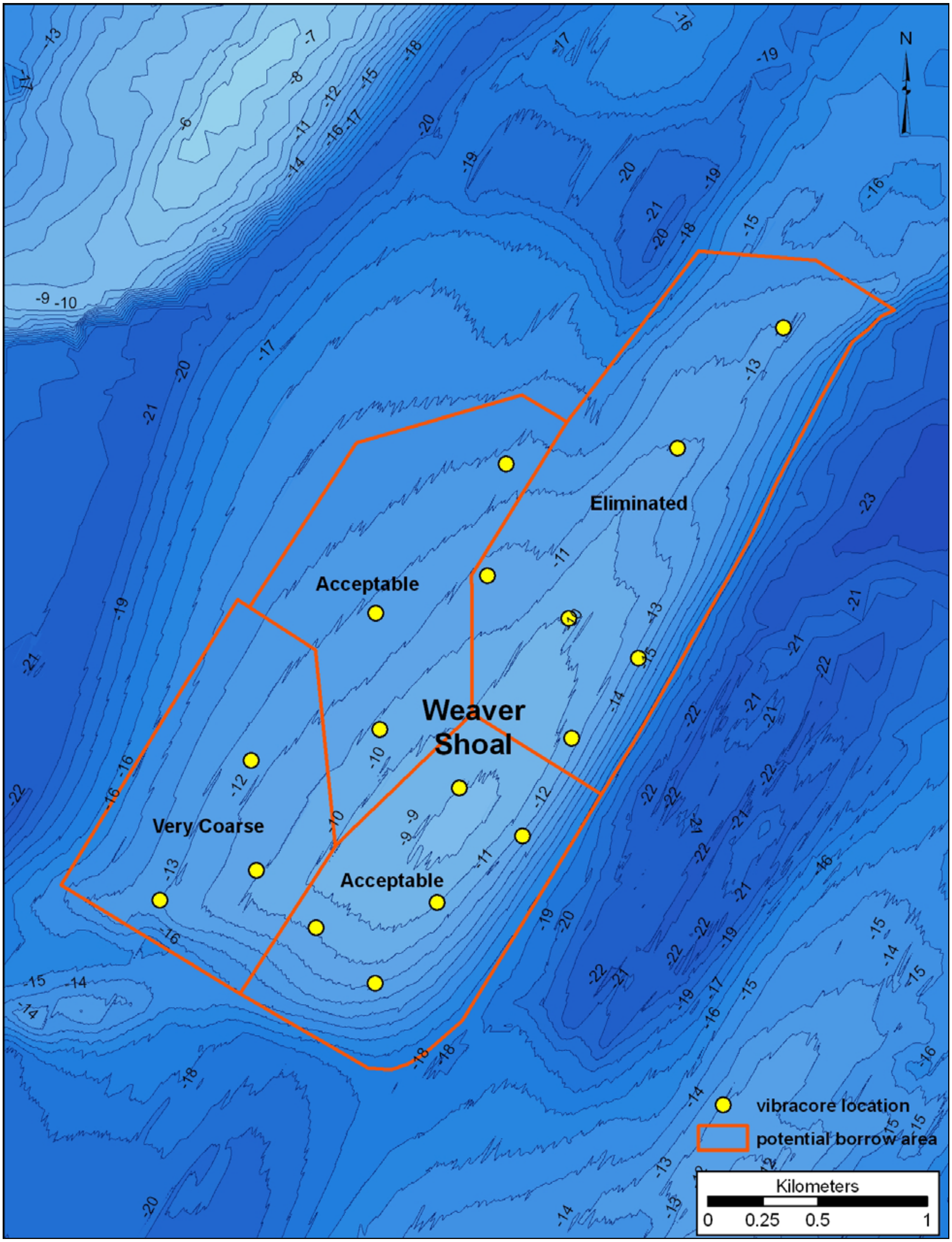


Figure 5.2. Weaver Shoal sand resource acceptability classification by USACE (2008).

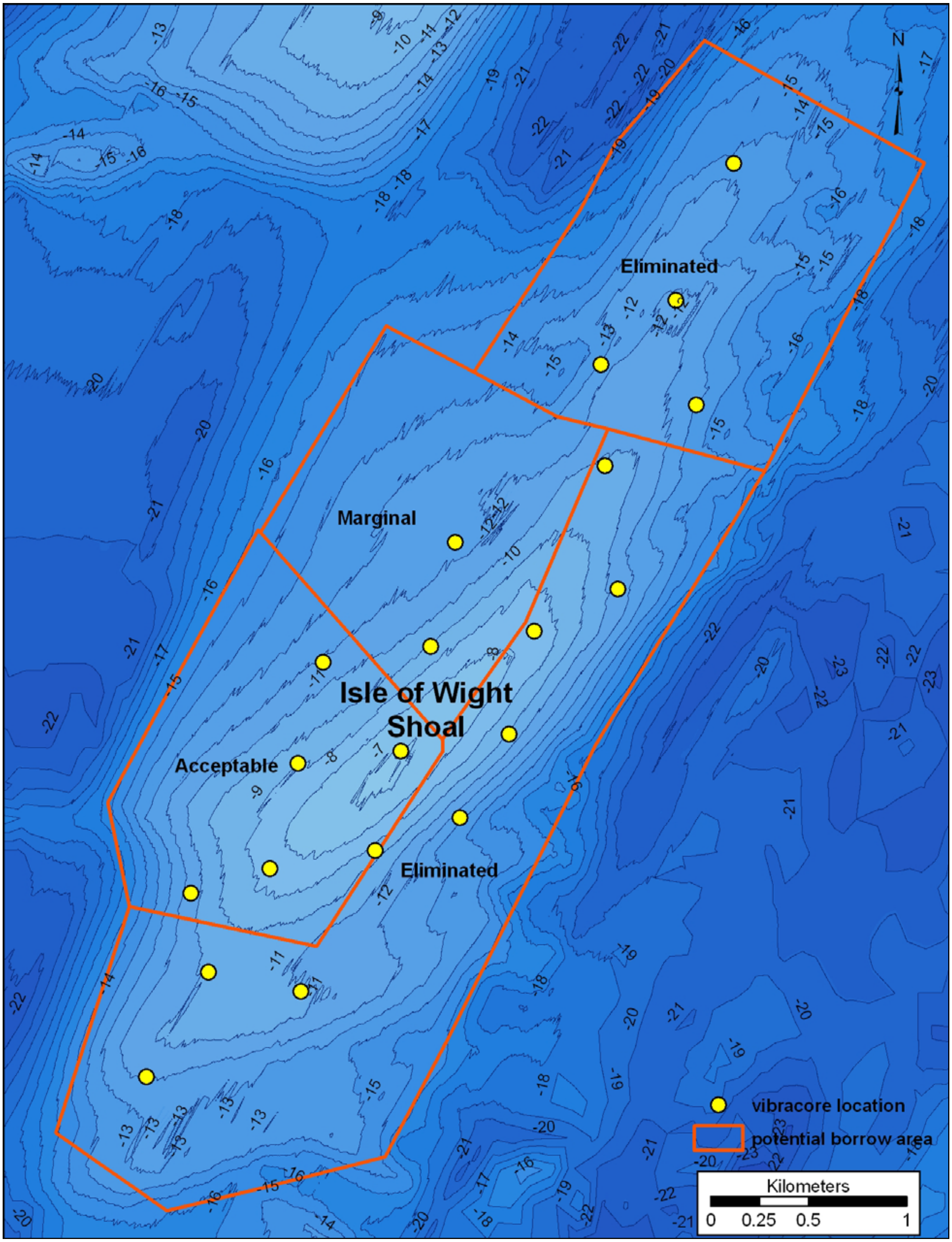


Figure 5.3. Isle of Wight Shoal sand resource acceptability classification by USACE (2008).

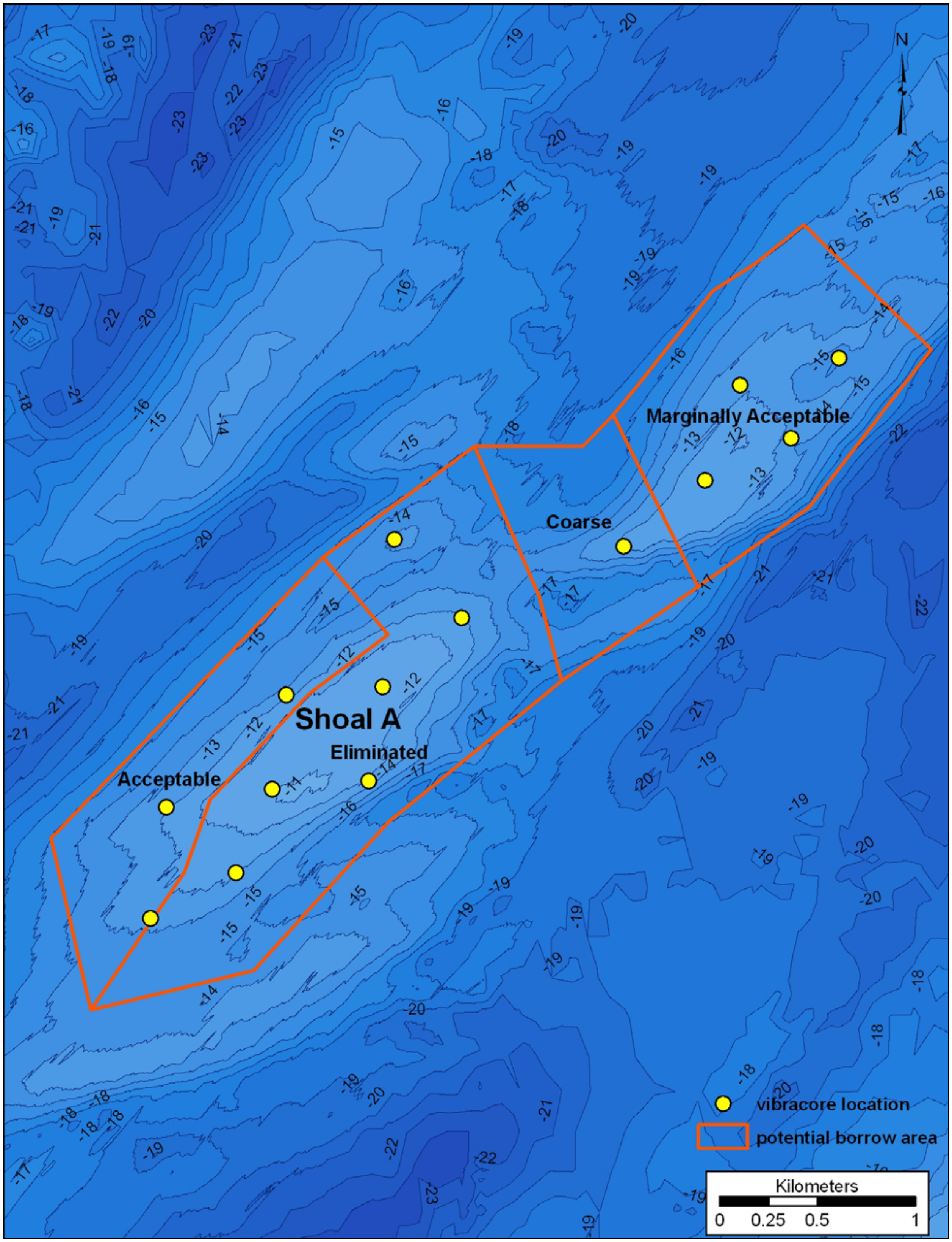


Figure 5.4. Shoal A sand resource acceptability classification by USACE (2008).

Weaver Shoal is the most northern shoal to evaluate. The mapped area is approximately 4 km long and 2 km wide. Vibracore sample analysis identified two parts of the shoal that contain acceptable sand for beach nourishment; the crest and leading edge and the northern half of the trailing edge. Isle of Wight Shoal is located 4 km to the southwest of Weaver Shoal. It is 6.5 km long and 2 km wide. Sand samples from this feature revealed the southeastern part of the trailing edge and the crest of the shoal to contain sand acceptable for beach nourishment. Shoal A is located 6.5 km to the southeast of Isle of Wight Shoal. The mapped area is 5 km long and 1.5 km wide. Vibracore samples extracted from the shoal identified only the southern two-thirds of the trailing edge of the shoal to be compatible with beach sand on Fenwick Island.

5.1.2 Alternative Excavation Scenarios

Concerns regarding sand removal effects on physical processes and biological habitat prompted USACE (2008) to recommend restrictions regarding sand dredging along shoal crests shallower than 30 feet. Based on shoal characteristics defined in USACE (2008), four potential dredging scenarios were developed for evaluating changes in physical processes on shoals containing acceptable sand deposits for beach nourishment along Fenwick Island. Specific numerical excavation scenarios include

- dredging a hole over a designated area on the shoal;
- dredging the leading edge of a shoal;
- dredging the trailing edge of a shoal; and
- dredging in a striped pattern to facilitate recruitment of benthic invertebrates into dredged areas.

Table 5.1 describes dredging scenario characteristics for each shoal based on USACE beach nourishment requirements, and **Figure 5.5** shows the locations of each scenario. All potential scenarios were located in shoal areas marked “acceptable” by USACE (2008) for dredging. Datasets representing numerically excavated bathymetry were created for each scenario. **Figures 5.6** through **5.13** illustrate three-dimensional renderings of shoal bathymetry after a specified amount of sand was removed from each of the shoals.

Table 5.1. Potential dredging scenario characteristics.

Shoal Name	Sub-Area	Removal Type	Seafloor Change (see Figure 3.1)	Excavation Depth (m)	Removal Volume ($x10^6$ cu m)
Weaver	Crest	Hole	None	3	1.3
	Crest	Striped	None	4	1.7
	Leading edge	Slice	Deposition	2	1.4
Isle of Wight	Crest	Hole	Minimal Deposition	2	1.5
	Crest	Striped	Minimal Deposition	4	1.4
	Trailing edge	Slice	None	2	1.7
Shoal A	Trailing edge	Hole	Minimal Erosion	2	1.4
	Trailing edge	Striped	Minimal Erosion	3	1.1
*Striped scenarios include five dredging strips that are 50 m wide and 50 m apart.					

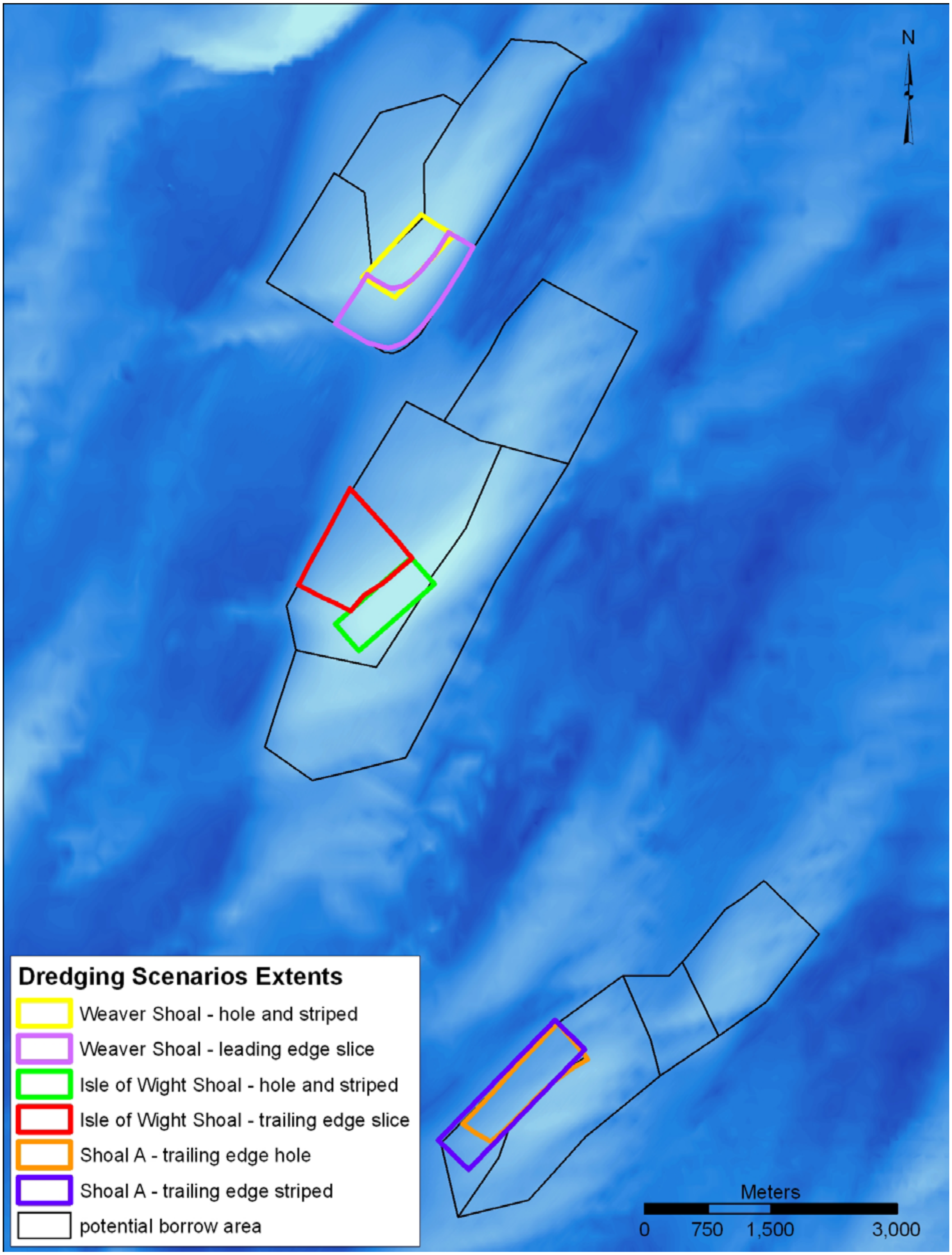


Figure 5.5. Areal extents of modeled dredging scenarios for each shoal.

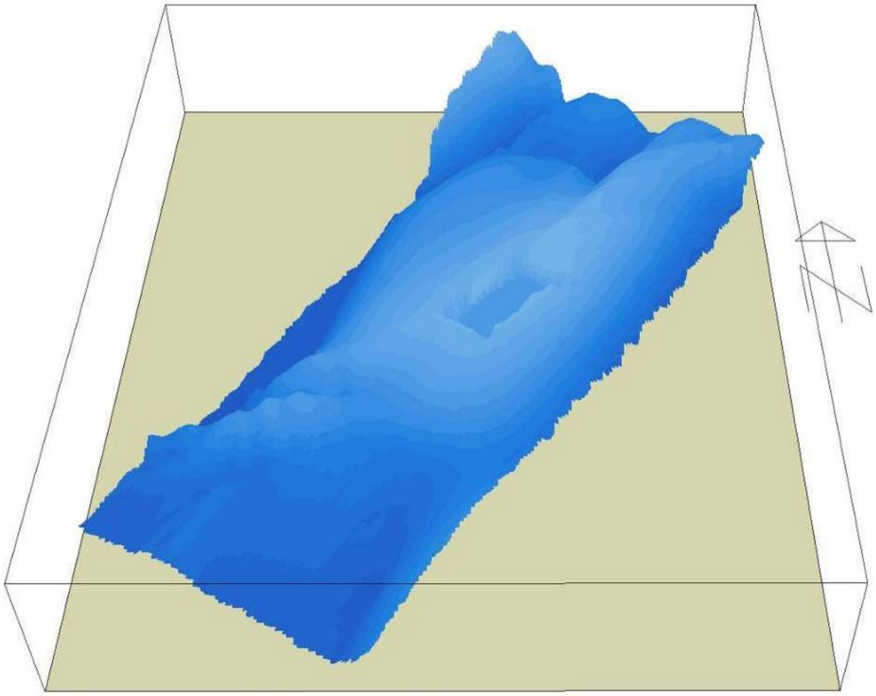


Figure 5.6. Weaver Shoal – hole excavation on shoal crest.

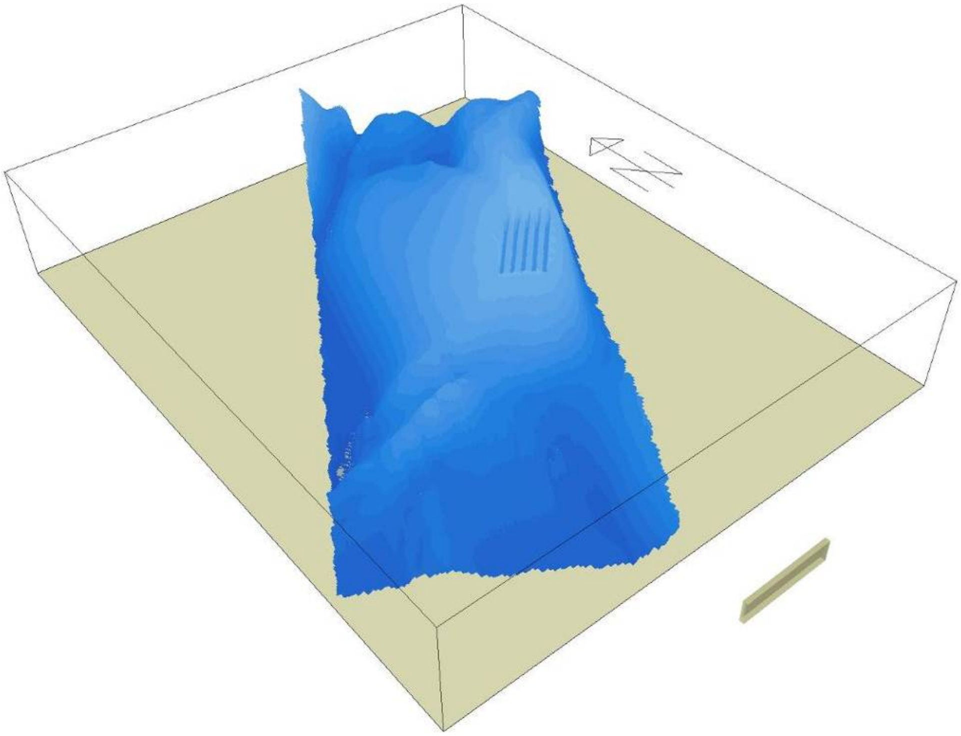


Figure 5.7. Weaver Shoal – striped area excavation on shoal crest.

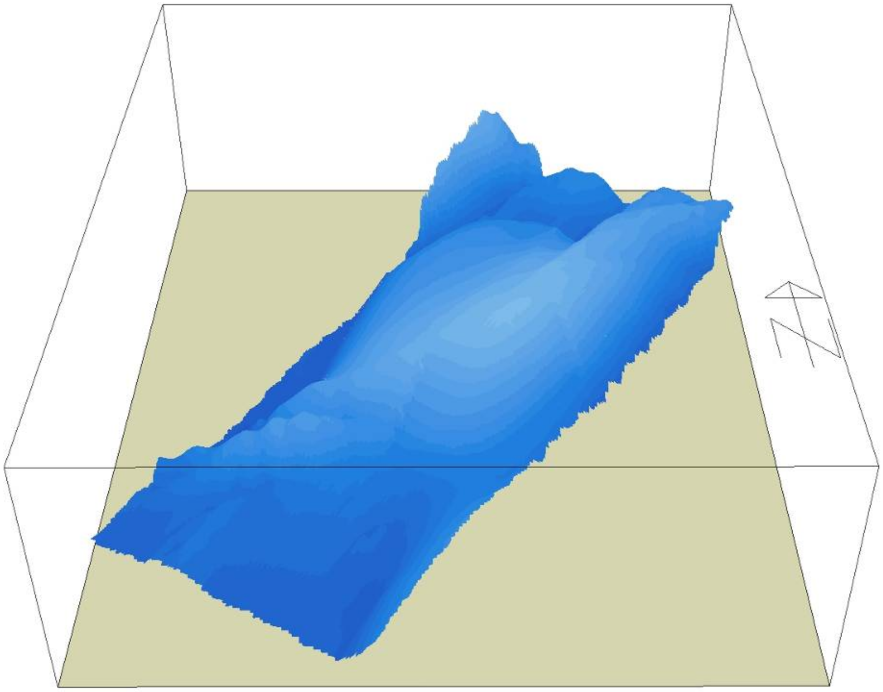


Figure 5.8. Weaver Shoal – leading edge excavation (slice).

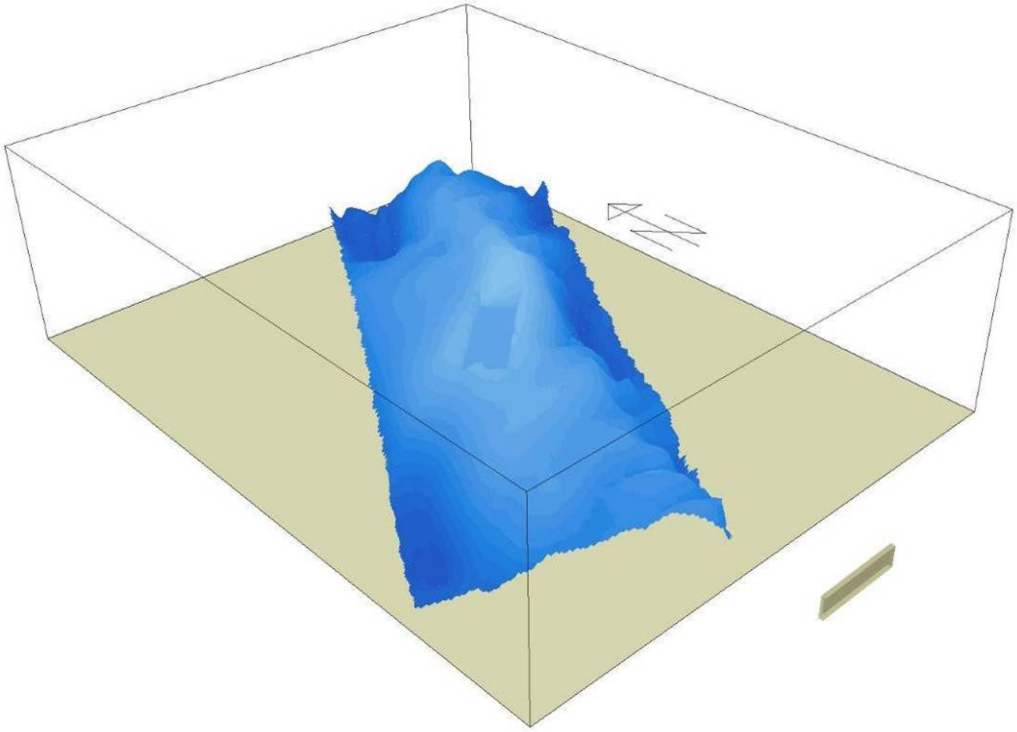


Figure 5.9. Isle of Wight Shoal – hole excavation on shoal crest.

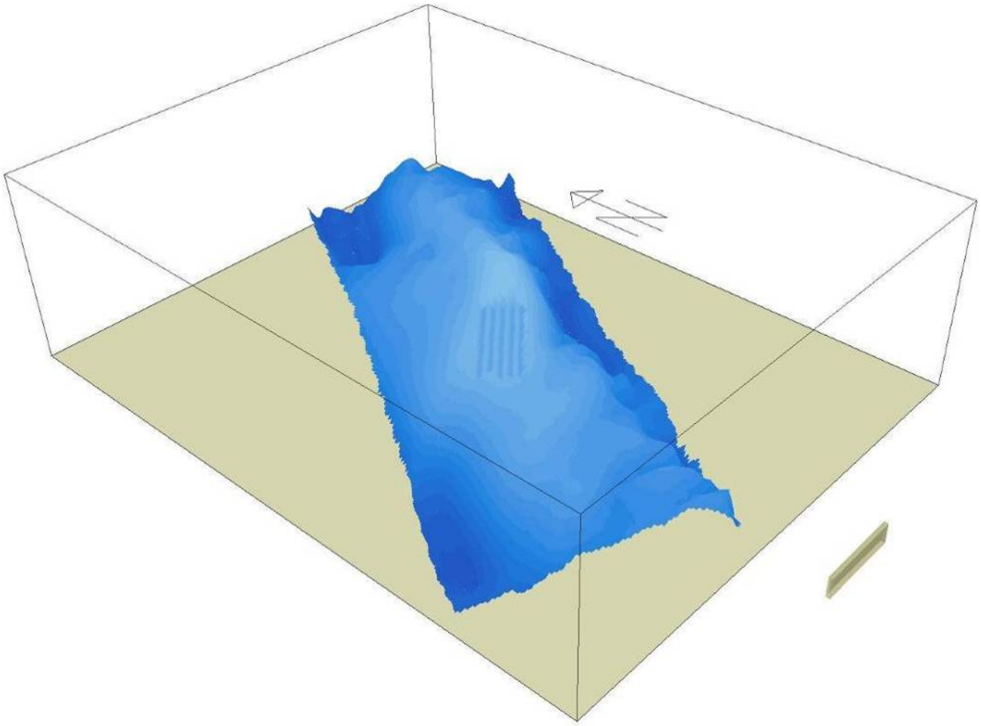


Figure 5.10. Isle of Wight Shoal – striped area excavation on shoal crest.

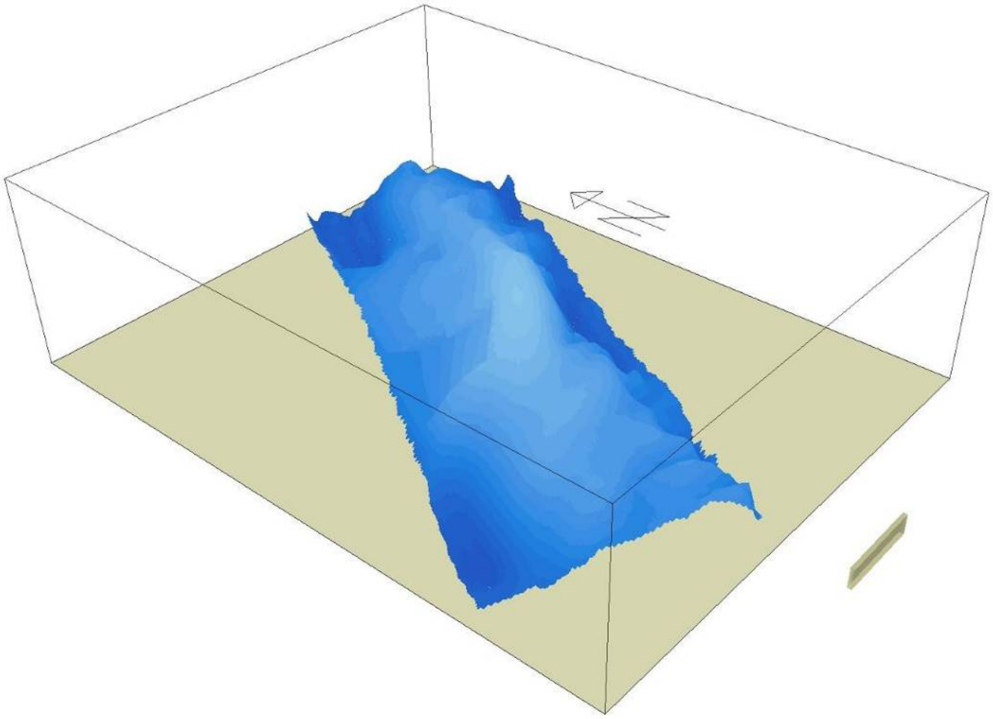


Figure 5.11. Isle of Wight Shoal – trailing edge excavation (slice).

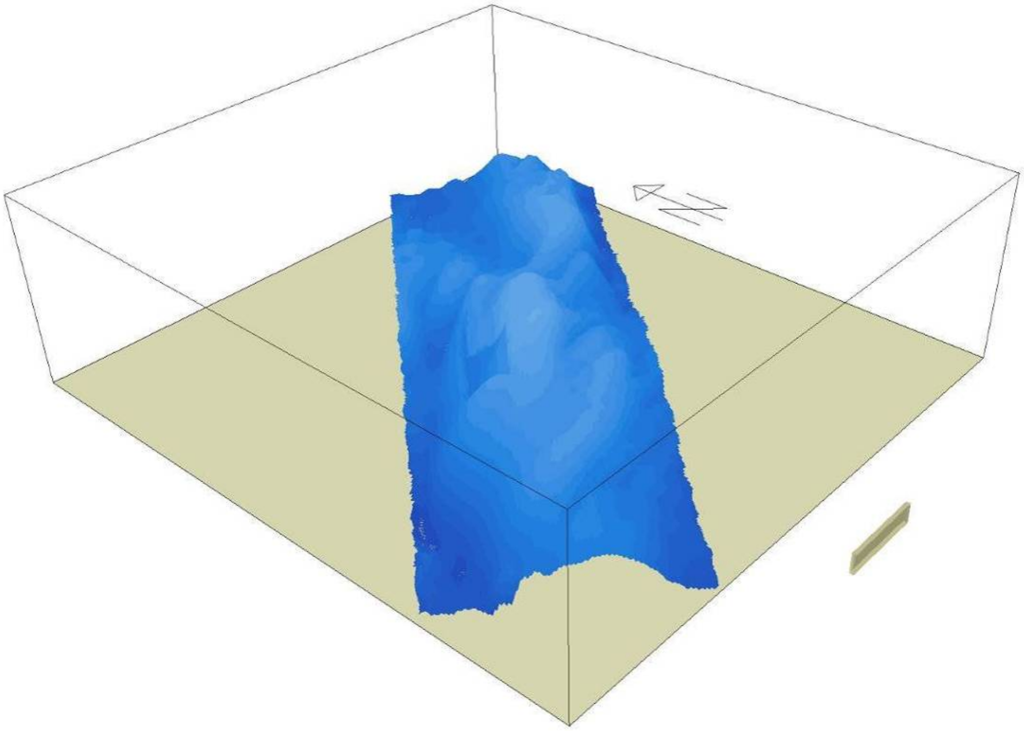


Figure 5.12. Shoal A – trailing edge excavation (hole).

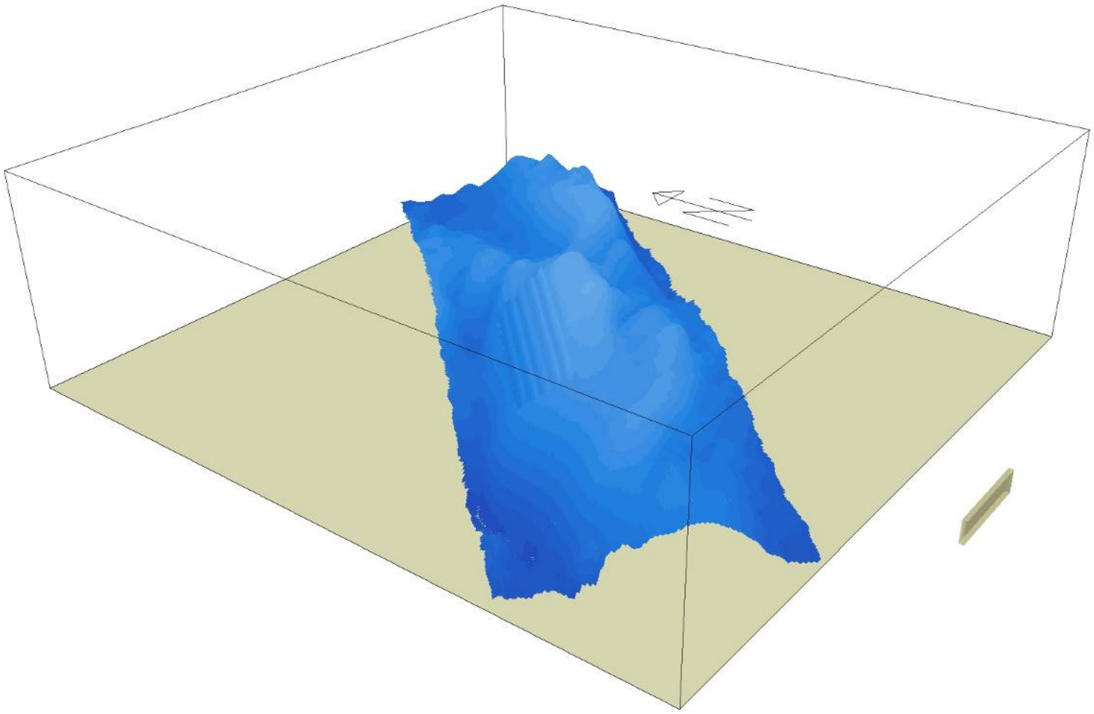


Figure 5.13. Shoal A – striped area excavation on trailing edge of shoal.

For each of the scenarios listed in **Table 5.1**, the following output is provided from numerical simulations:

- Sediment deposition/erosion contours;
- Visual representation of seafloor change;
- Borrow site infilling for imposed storm conditions; and
- Circulation pathways (arrows).

Although one would like to believe that quantities derived from numerical modeling simulations are absolute, sediment transport and geomorphology modeling are not advanced enough to provide accurate estimates for most derived quantities. Models will always produce numbers, but often these numbers are associated with uncertainties of +/- 100%. The greatest benefit of using numerical models is their ability to correctly reproduce patterns of flow and sediment transport (information) relative to actual measurements (data). For example, pre- and post-dredging comparisons will provide an understanding of impacts associated with sand extraction, but the absolute magnitude of change (e.g., cm/day) is not nearly as important (or reliable) as the percentage of change. A great deal of useful information will be derived from numerical modeling results, but limitations must be recognized.

5.2 NEARSHORE HYDRODYNAMICS, WAVE PROPAGATION, AND MORPHOLOGICAL MODELING

The interaction between waves and currents on the inner continental shelf results in net sedimentation patterns recorded on the shelf surface and at the shoreline. Sand shoals and intervening swales that formed and evolved on the shelf surface over the past 5,000 years create regions of wave energy focusing and divergence, shelf circulation patterns constrained by the extent and orientation of these shelf features, and important biological habitat for many fish species and benthic communities (Byrnes et al., 2000; USACE, 2008). Extraction of sand from specific shoals may be advantageous for beach nourishment purposes, but an evaluation of potential physical and biological impacts of suggested sand mining scenarios must be evaluated to ensure that adverse environmental impacts are minimized. In the absence of years of monitoring measurements to assess potential impacts of sand borrow site excavation, numerical modeling procedures developed by the USACE (Buttolph et al., 2006) were applied to document potential physical environmental impacts of offshore sand mining. The following discussion describes the procedures used and results determined for specific sand extraction scenarios constrained by the physical characteristics of sand borrow sites as documented by the Baltimore District of the USACE for sand shoals offshore Fenwick Island, Md. (USACE, 2008).

5.2.1 Overview of Regional Hydrodynamics

Tides in the Mid-Atlantic Bight are semi-diurnal, having roughly two high and two low water levels each day. Neap tides in the Ocean City area have an amplitude of approximately 1 m, while spring tide range increases slightly to about 1.2 m. A 6-day record of tides for NOAA Station 8570280 (Ocean City) is shown in **Figure 5.14**. The diurnal inequality is quite small. Primary tidal datums for Station 8570280 (Ocean City Fishing Pier; 1983-2001 Epoch) are summarized in **Table 5.2**.

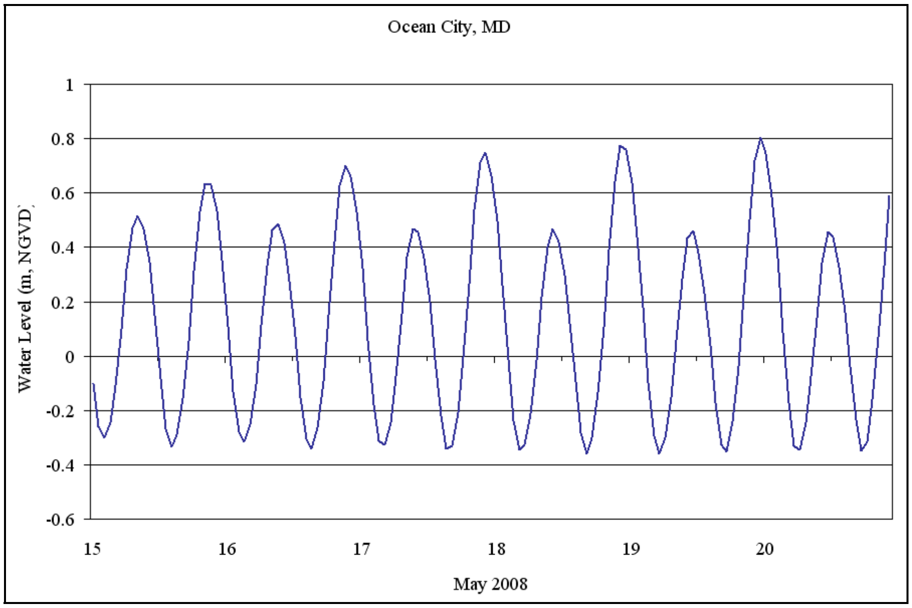


Figure 5.14. Typical semi-diurnal tidal signal from NOAA water level recording Station 8570280 at the Ocean City Fishing Pier, Md.

Table 5.2. Reference datums for Ocean City, Md., NOAA Station 8570280.

Datums	Elevation (m)
Mean High Water (MHW)	0.66
North American Vertical Datum of 1988 (NAVD 88)	0.29
Mean Sea Level (MSL)	0.15
National Geodetic Vertical Datum of 1929 (NGVD)	0.00
Mean Low Water (MLW)	-0.37

In addition to this forcing from tidal potential, shelf waters along the Mid-Atlantic Bight are subject to atmospheric forcing as well, whereby wind stress and pressure gradients can result in surface flow, which is independent of tides. Freshwater outflow from the Delaware Bay can result in a density-driven current that moves generally to the southwest, passing over the study area (Chapman and Beardsley, 1989). This local influx of freshwater can be understood as a component of the much larger scale shelf flow, whereby freshwater influx from glacial melt and river runoff in southern Greenland generates a buoyancy driven current, which travels more than 5,000 km along the Labrador coast, around Newfoundland and the Scotian Shelf, and along the Mid-Atlantic Bight, ultimately being entrained in the Gulf Stream offshore North Carolina (Beardsley and Winant, 1979).

Shelf water across the Mid-Atlantic Bight will have a steadier southwest-directed flow during autumn and winter months, with fewer instances of reversal compared with summer (Bumpus, 1973). The average velocity of this net southwesterly flow is roughly 5 cm/s but can reach maximum speeds approaching 20 cm/s. During times of extended southerly winds or low freshwater runoff, there can be reversals of the surface current, whereby flow is directed to the north.

Shear stress from wind blowing on the surface of the water can have a strong influence on coastal circulation, and in turn, the temperature and salinity profile through the water column. During winter months, a low pressure system dominates winds over the Atlantic coast, generating relatively strong average winds of about 4 m/s from the west and northwest. As the northern hemisphere becomes warmer during late spring, the Bermuda high pressure system will strengthen and become the dominant force shaping regional wind patterns in the study area. This high pressure system results in average daily winds in the range of 2 m/s, typically from the southwest.

The scope of the present study is far to narrow to include modeling of these large-scale shelf processes, but various sources of nontidal forcing and specifically a background flow generally directed to the southwest should be acknowledged when considering the results that follow.

5.2.2 Overview of Regional Wave Conditions

The interaction of wind with the water surface generates waves. Once wind waves are generated, the forces of gravity, and to a lesser extent surface tension, allow waves to travel long distances across the sea surface. Waves play a vital role in moving sand along the shoals and shaping morphological changes that occur. As such, a proper estimation of wave energy is fundamental to estimating the potential effects that offshore dredging will have on the future morphology of the shoal complex.

As waves enter the nearshore zone, variable seafloor morphology causes wave characteristics (e.g., height and direction of travel) to change. As waves enter shallow water, their height increases (shoaling), and the direction of travel is influenced by variable water depths present along the shoal (refraction). There is a limit to how shallow water can get and still have a wave remain intact. Eventually wave steepness causes the wave to become unstable and break, which dissipates wave energy. Energy also is distributed along a wave crest by a process called wave diffraction. Together, wave shoaling, refraction, diffraction, and breaking all influence sediment transport and morphology changes observed on the shoal.

5.2.2.1 Availability of Wave Data

The USACE Wave Information Study (WIS) has met a critical need for wave information in coastal engineering studies since the 1980’s. WIS contains time-series information of spectrally-based significant wave height, peak period, peak direction, and wind speed and direction produced from a computer hindcast model. The hindcast wave model, WISWAVE (Resio and Tracy, 1983), is run using wind data (speed and direction) at selected coastal locations around the United States. The model provides wave climate based on local/regional wind conditions. Because these data are numerically generated, consistent and long-term wave data are available at most coastal locations.

Selection of the Offshore Boundary Conditions from the WIS Record

Figure 5.15 illustrates the location of WIS stations (yellow markers) that lie within the project area. It is desirable for the offshore boundary of the wave model to fall at the same longitude as the WIS stations, so that no wave transformation need be performed to apply WIS data to the offshore boundary of the model. The inshore line of WIS stations is located too far inshore to be of use as boundary conditions, with WIS Station 162 falling exactly on top of Weaver Shoal. To ensure that wave refraction and shoaling across the shoals were modeled in detail, the outer line of WIS stations was used to select a boundary condition. Station 161 is located offshore Weaver and Isle of Wight shoals, while Station 163 is adjacent to Shoal A. A comparison of wave roses for WIS Stations 161 and 163 is shown in **Figure 5.16**.

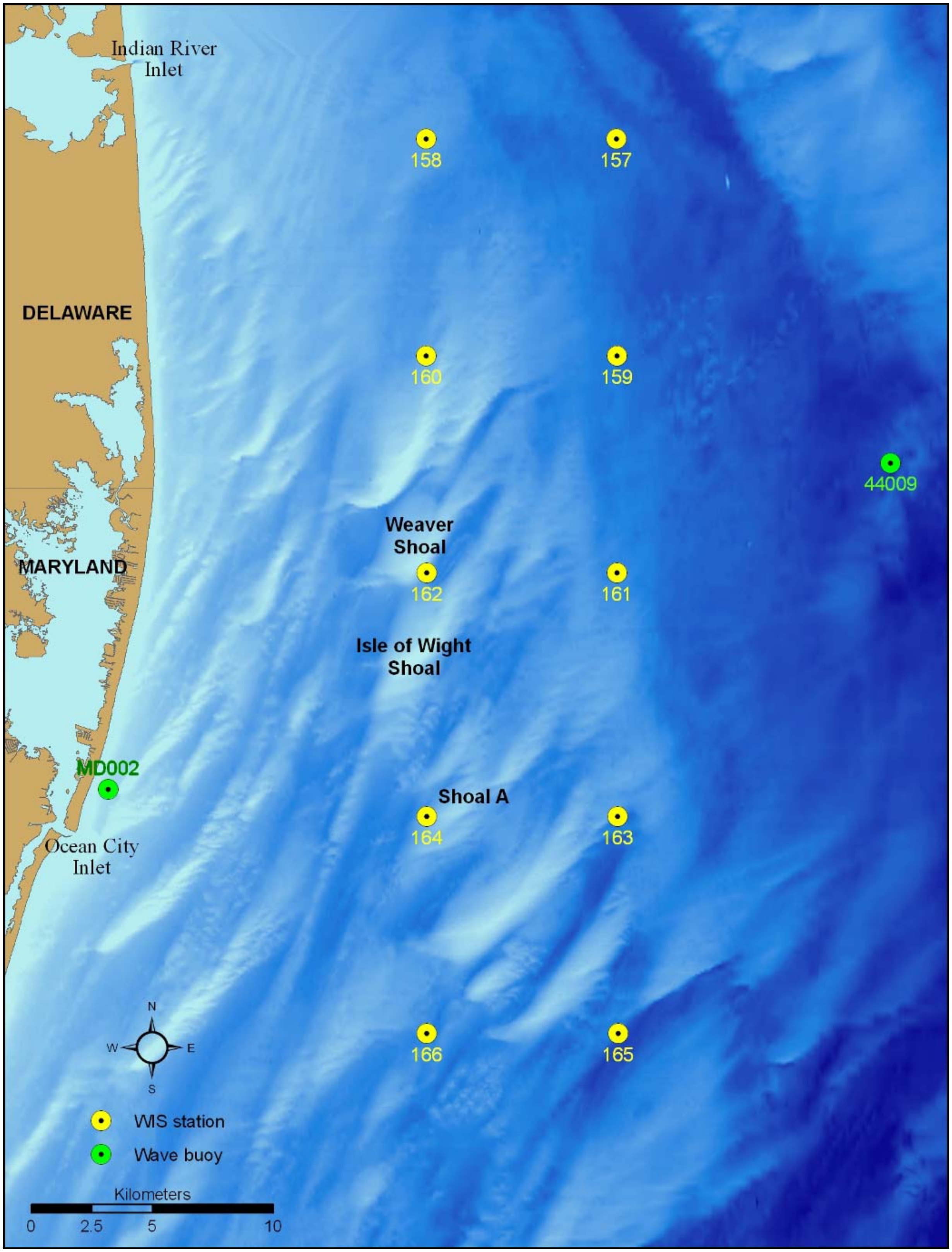
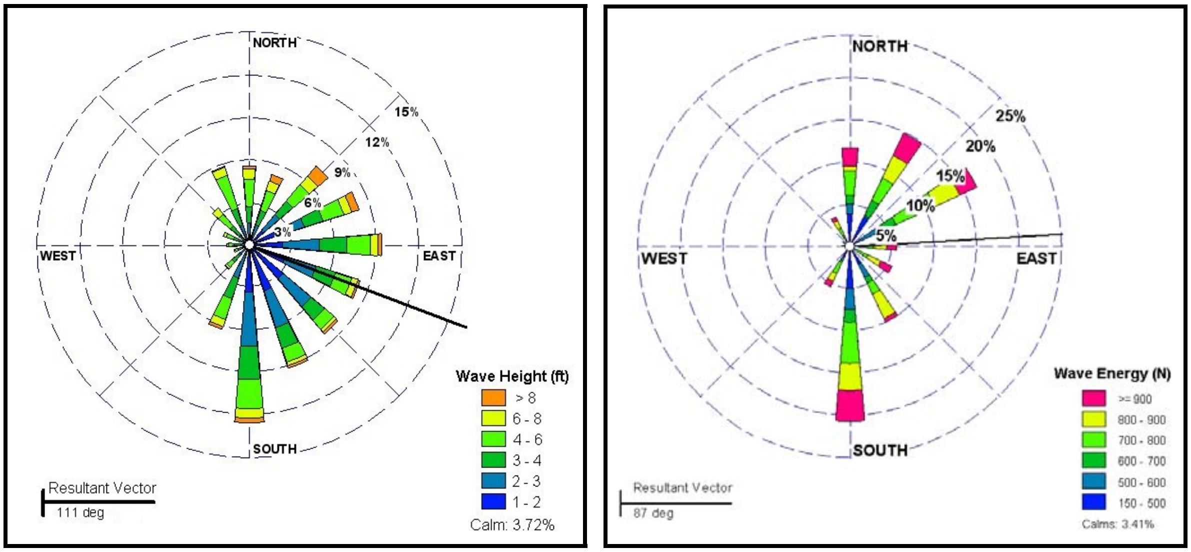


Figure 5.15. WIS stations in the study region are shown with yellow markers. USACE Wave Gage MD002 and NDBC Buoy 44009 are shown in green.

WIS 161



WIS 163

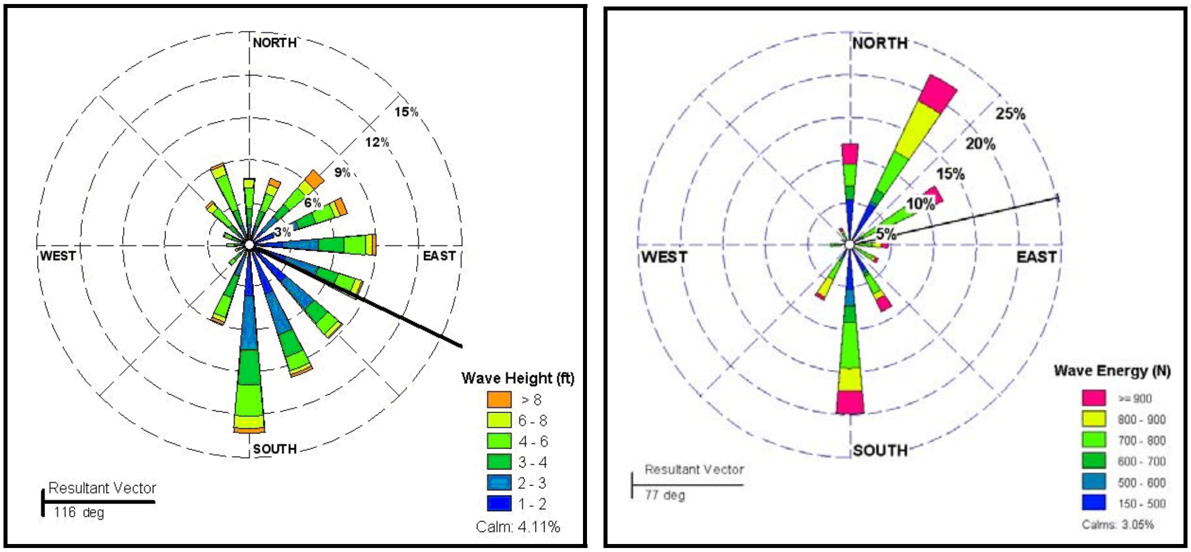


Figure 5.16. Wave height and energy roses for WIS Stations 161 and 163.

These plots confirm that a majority of the wave energy offshore of the shoal complex is incident from the northeast and the southeast. Moving from north to south, there is a slight increase in the percent occurrence of waves from the north, but these differences are quite small. It is interesting to note that while the largest waves (orange in the figures) are predominantly incident from the north, a majority of all waves are from the southeast. This indicates that under typical conditions, waves are incident from the south and southeast, while the largest storm events arrive at the shoals from the northeast.

For the given longitude, it is accurate to say that wave climate immediately offshore the study area is spatially consistent. As a result, it was decided to apply the wave model with data from a single WIS station rather than impose a spatially varying offshore wave condition. WIS

Station 161 was chosen to provide the wave data used as a boundary condition for all wave runs.

Verification of WIS Data

Wave measurements made by NOAA during the 1980's made verification of WIS results possible by comparing the statistics and the distributions of wave heights and periods for different time periods (Hubertz et al., 1993). Improvements have been made through subsequent modeling efforts to increase the accuracy of WIS results relative to NOAA measurements. Second Generation (2G) WIS data, which accounts for weak nonlinear wave-wave interaction, equilibrium spectral functions, refraction, shoaling and dissipation, were used in the present study. The 2G WIS data provide wave parameter results every hour. A detailed comparison between the 2G WIS data, the Third Generation (3G) wave models, WAM and WAVEWATCH III, and the relevant National Data Buoy Center (NDBC) stations can be found in Tracy and Cialone (2004). The findings from that work are as follows:

The 2G WIS results are consistent with results from the more complex calculations done in the 3G models. No one model is the clear winner in these comparisons. The 3G models tend to have slightly better directional results. WIS tends to slightly over-predict wave height, and the 3G models tend to under-predict. WIS captures storms and hurricane events quite well. Analysis of peak wave periods showed that all models tested could stand to improve their predictions in this regard.

To supplement the regional scale verification referenced above, current work also compared the 2G WIS data with an inshore NDBC buoy location nearby the area of interest. WIS Station 161 and NDBC Buoy 44009 are located approximately 11 km from each other (see **Figure 5.15**).

Wave data were recorded at the buoy between 1986 and present. Data from 1990 were chosen to compare WIS and NDBC results. The comparison of wave heights for this time period is shown in **Figure 5.17**. Both data sources reported wave heights at 1-hour intervals.

WIS results reproduce the trend of NDBC-measured data fairly well, but a slight bias in wave height is indicated. WIS data appear to slightly over-predict wave heights under storm conditions and under-predict during calmer periods. The overall average indicates that WIS data under-predict measured wave height by an average of 0.13 m. It should be noted that the NDBC buoy is located further offshore than WIS Station 161. The buoy lies in 28 m of water, while the location of Station 161 shows a water depth of 21 m. Considering the distance between the two locations, wave refraction and breaking could account for much of this difference.

Despite the apparent difference in wave height between WIS Station 161 and NDBC Buoy 44009, the availability and continuity of WIS hindcast data make it an attractive choice when considering different sources for regional wave conditions. Because the data are widespread and continuous, absent accurate field data from very near the site, the 2G WIS data are the best option for the development of spectral boundary conditions.

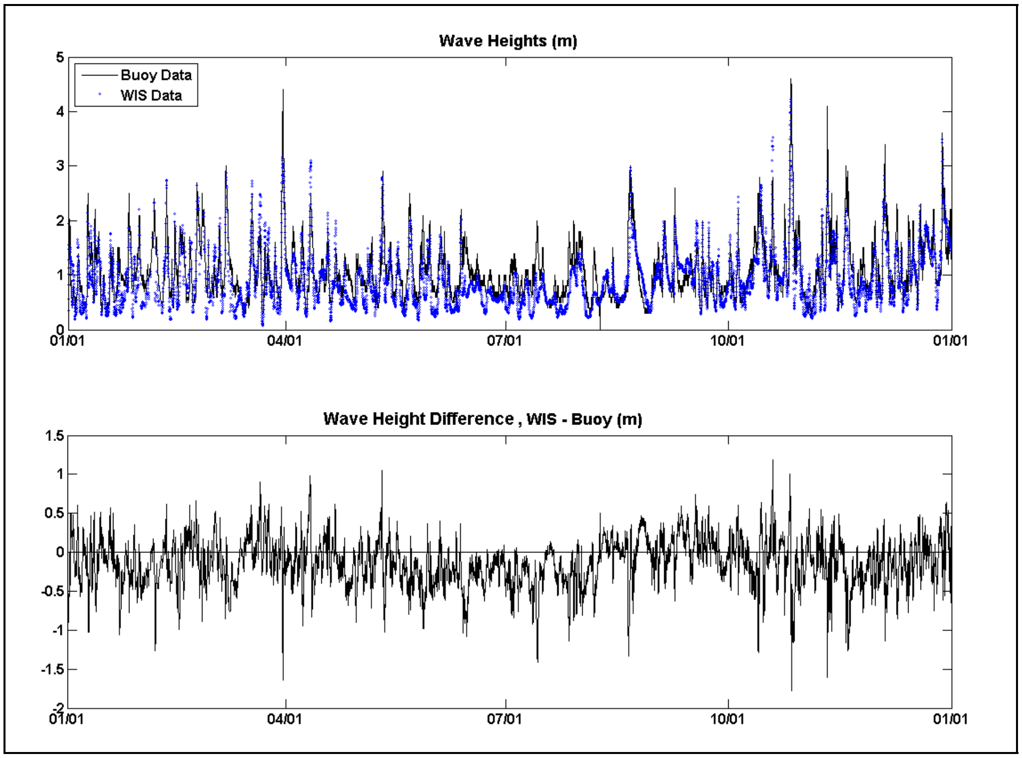


Figure 5.17. Wave height comparison between WIS Station 161 and NDBC Buoy 44009 for 1990. The top panel illustrates a time series of wave heights for each station, while the bottom panel shows the difference between WIS and NDBC results as WIS prediction - buoy measurement.

5.2.3 Hydrodynamic Modeling

ADCIRC – A regional hydrodynamic model for the study area was created for this work using the Advanced Circulation Model for Oceanic Coastal and Estuarine Waters, or ADCIRC. ADCIRC is a two-dimensional, depth-integrated circulation model (Luettich et al., 1992). The model domain is described by a collection of finite elements that give the model excellent flexibility to cover large domains and provide the detail required for areas where strong flow variations are expected. Computational features of ADCIRC include variable Coriolis forcing, wetting and drying, choice of bottom stress model, and detailed user control over model output.

5.2.3.1 Model Domain

Figure 5.18 illustrates the model domain for the mid-Atlantic coast. Land boundaries are shown in brown, islands are green, and open boundaries are blue. The model was forced at a single open boundary running offshore from central New Jersey to North Carolina. The final model mesh contains 7,043 nodes and 12,141 elements.

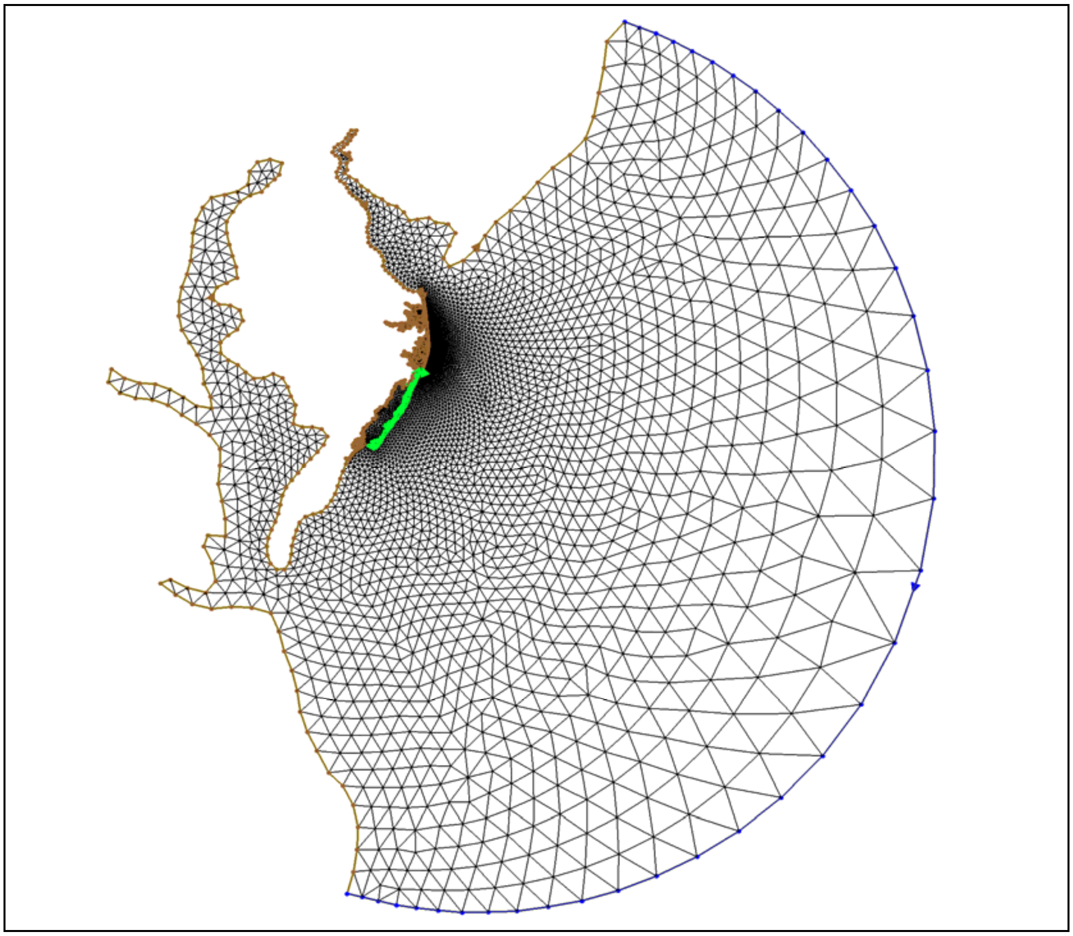


Figure 5.18. ADCIRC model domain for the mid-Atlantic coast. The offshore boundary is shown in blue, land boundaries are brown, and islands are green.

5.2.3.2 Boundary Conditions

ADCIRC allows various forcing options for driving flow in the model, including a time series of water-surface elevation, tidal constituents, a time series of flow rates, and wind stress and atmospheric pressure. Tidal constituent forcing was applied to open boundaries, and tidal potential forcing was applied to the interior of the domain for hydrodynamic simulations. Freshwater inflows at Delaware Bay, Chesapeake Bay, and from the Delmarva Peninsula were not included in the model due to the 2-D depth averaged solution being unable to model 3-D stratified flow conditions.

The tidal constituent values for the open boundary were extracted from the existing Western North Atlantic Tidal Database. This provided constituent data for the M2, S2, N2, K1, O1, Q1, P1, K2, M4, and M6 components of the tide.

Atmospheric pressure changes and local winds have a significant influence on water levels within the study area. The relatively shallow offshore shelf means that atmospheric forcing can often result in changes in water level that are the same order of magnitude as pure tides. However, these atmospheric forcings were not included in the current study. The amount of data required to properly include these aspects into the modeling effort is quite large. Such a detailed undertaking is beyond the present scope of this study.

5.2.3.3 Model Calibration

The primary purpose for employing the regional hydrodynamic model ADCIRC was to provide a time series of water surface elevation as a boundary condition for detailed morphology modeling (discussed below). A match of tidal amplitude and phase seaward of Ocean City was deemed sufficient for the purposes of describing typical flow patterns along the shelf in the study area. The model mesh and bathymetry, as well as the location of the field data station, are shown in **Figure 5.19**.

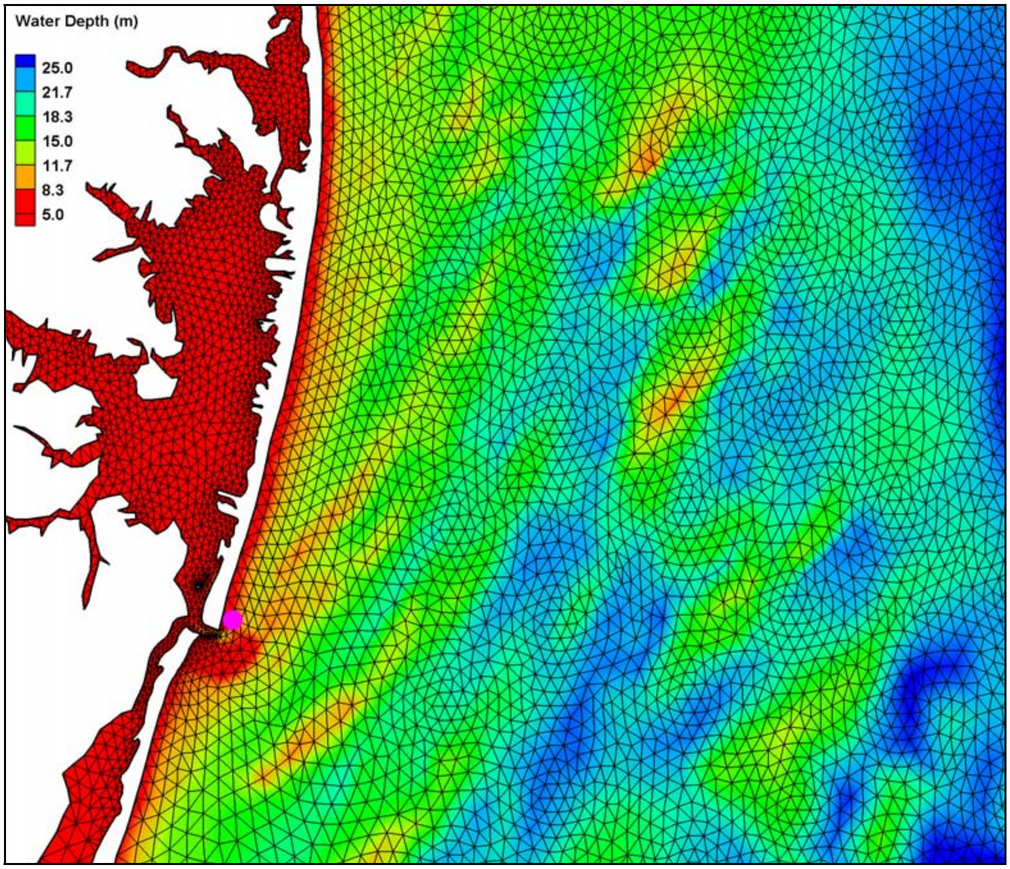


Figure 5.19. Detail of the ADCIRC model domain focused on Ocean City, Md. Bathymetry contours are shown in color, overlain with model mesh for this region. The NOAA tidal recording station used to calibrate the model is shown as a purple dot.

To limit the influence of the atmospheric signal in field data, the tidal record was searched for a period that had no storms and relatively low winds. Spring dates were also avoided to eliminate all large freshwater outflow events from the Delaware Bay. Ultimately, the period from 1-10 October 1991 was chosen to simulate tidal circulation in the hydrodynamic model.

It would have been preferable to evaluate a more recent time period; however, the only tide station currently operational at Ocean City is Station 8570283 at the Coast Guard Station inside the inlet. The tide range inside the inlet is roughly 0.3 m smaller than outside and is not indicative of conditions at the study site. Historical tidal data were collected from the fishing pier at Ocean City (NOAA Station 8570280); however, this station was abandoned in November 1991. Because the entire focus of this regional scale hydrodynamic modeling was to recreate average tidal conditions used to drive the morphological model, these older data are the best for calibration purposes.

All simulations began on October 1, providing 3 days of run time prior to the period of interest. Plots of recorded versus modeled water levels for Ocean City are shown in **Figure 5.20**.

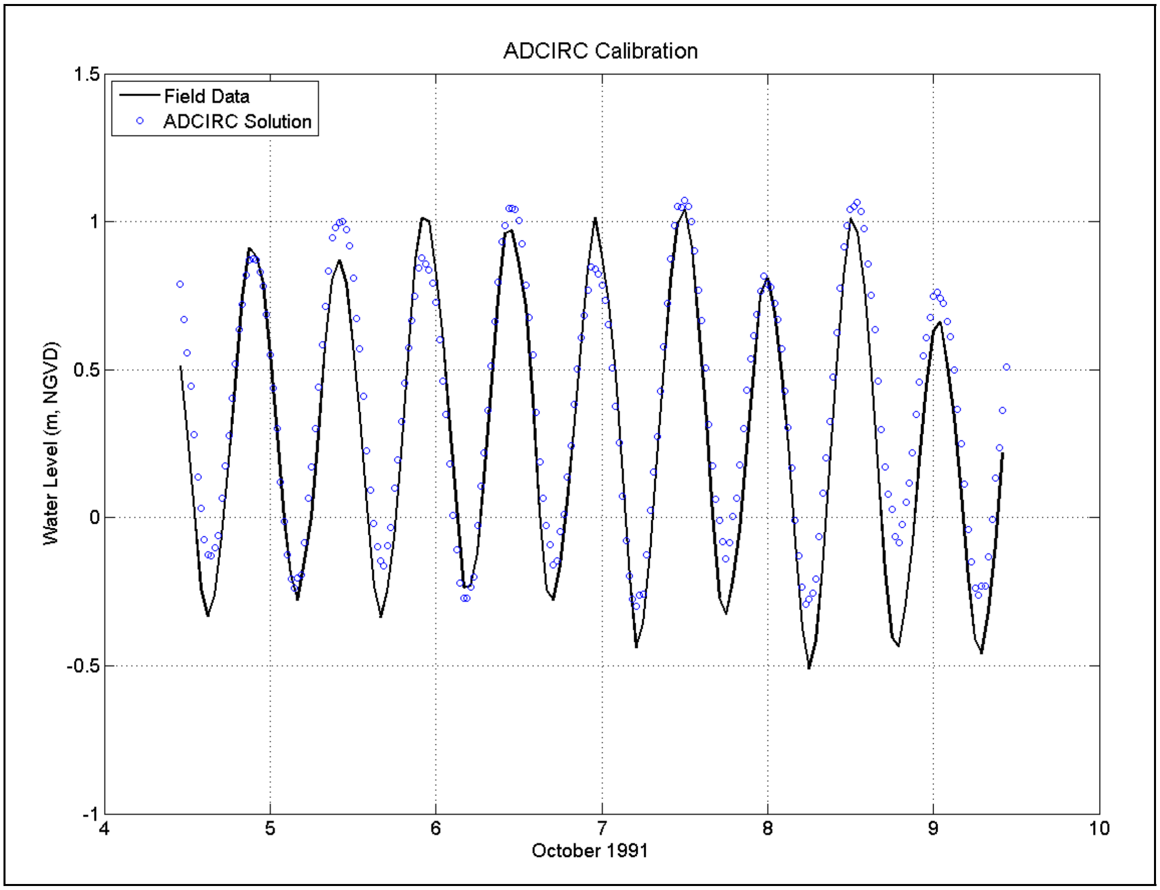


Figure 5.20. Comparison of simulated versus measured water levels for NOAA Station 8570280, 4 to 10 October 1991.

Figure 5.20 indicates fair agreement between the ADCIRC solution (blue circles) and the recorded tide data for NOAA Station 8570280 (black line). Accurate representation of average tidal conditions requires an evaluation of two vital tidal features: amplitude and phase of the tide. Comparison of measured data and modeled results reveals that both attributes are matched well. Model results show slight departures (0.1 to 0.2 m) from measured tidal elevations during the first 12 hours and final 36 hours of the time series. This discrepancy is due to nontidal forcing recorded in the field data. The most likely process causing nontidal water level changes at these times is wind stress. ADCIRC modeling for this project is driven by tidal potential only, so any phenomenon impacting water levels due to nontidal forcing does not show up in the model solution.

5.2.3.4 General Circulation Patterns

In addition to providing a time series of water surface elevations for calibration at a single point, ADCIRC results also provide an overview of flow patterns in the area. **Figures 5.21** and **5.22** illustrate current speed contours and direction for typical maximum flooding and ebbing events, respectively, near Ocean City Inlet. The locations of Weaver Shoal, Isle of Wight Shoal, and Shoal A are outlined as black rectangles for reference. While there are current speeds exceeding 1 m/s through the inlet throat, speeds are quite small in open water on the continental shelf. Maximum values simulated in the study area are on the order of 5 cm/s. Predicted direction of flow is observed to be north/northeast on a flooding tide and south/southwest on an ebbing tide. While this hydrodynamic solution is used as a boundary condition for morphological modeling discussed below, extremely small flow velocities across the study area suggest that waves are the predominant shaping force of shoals over short to medium time scales. It is probable that density driven flow to the south or other larger scale flows occurring along the shelf could be influencing morphology over time scales longer than the ones we have simulated in this study.

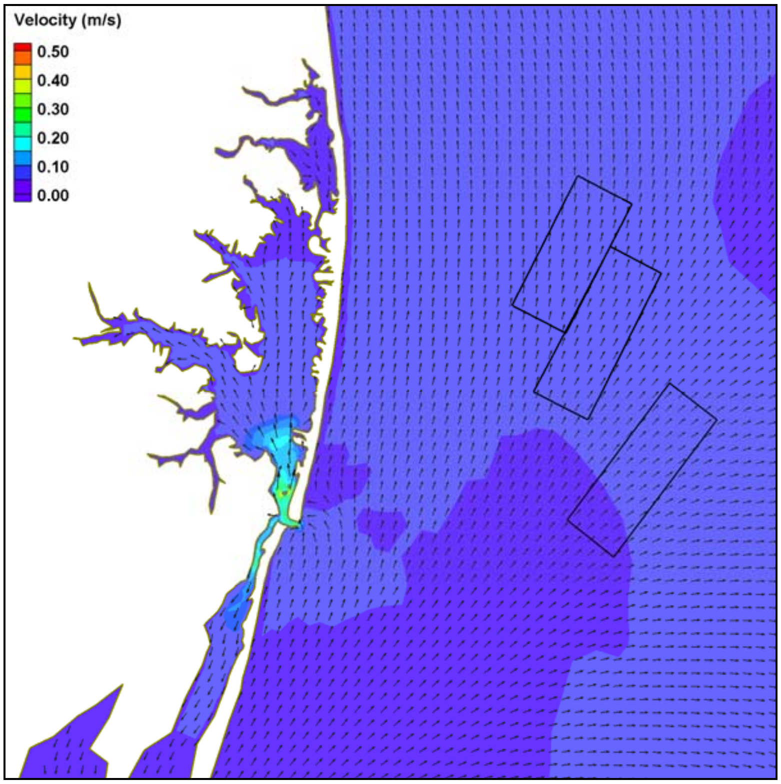


Figure 5.21. Current speed contours and direction vectors for maximum flooding tide at Ocean City Inlet, Md., 5 October 1991. Weaver Shoal, Isle of Wight Shoal, and Shoal A are framed as black rectangles for reference.

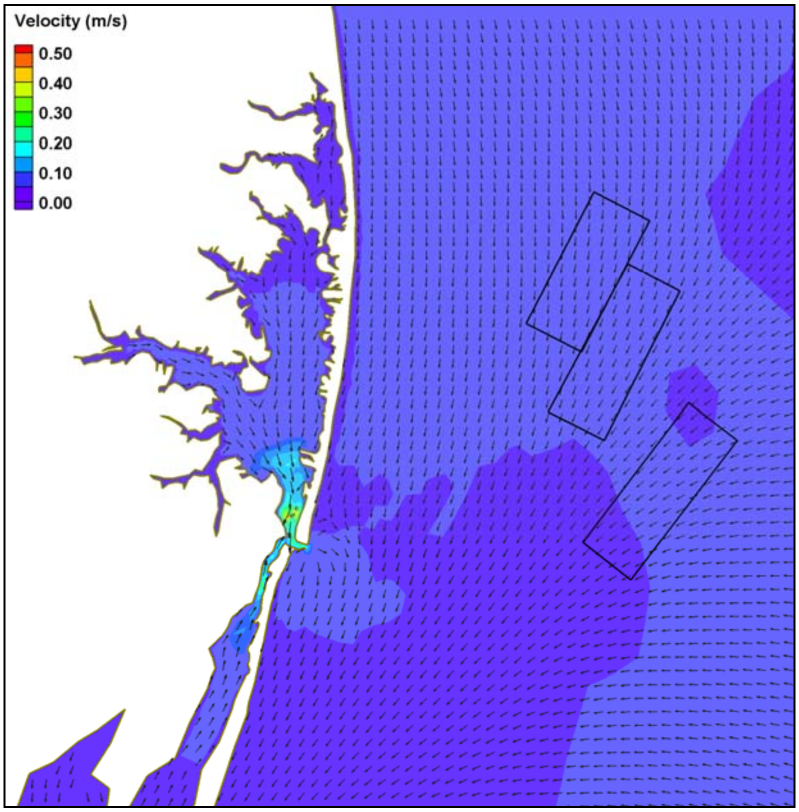


Figure 5.22. Current speed contours and direction vectors for maximum ebbing tide at Ocean City Inlet, Md., 5 October 1991. Weaver Shoal, Isle of Wight Shoal, and Shoal A are framed as black rectangles for reference.

5.2.4 Wave Modeling

Nearshore wave heights and directions across Weaver Shoal, Isle of Wight Shoal, and Shoal A were estimated using the USACE STeady-state spectral WAVE model (STWAVE) to simulate propagation of offshore waves across the area of interest. Offshore wave data available from WIS were used to derive input wave conditions for STWAVE. Results of wave modeling were used as input for estimating morphology changes within the study area.

STWAVE – STWAVE v. 4.0 is a steady state, spectral wave transformation model (Smith et al., 1999). Two-dimensional (frequency and direction versus energy) spectra were used as input to the model. STWAVE is able to simulate wave refraction and shoaling induced by changes in bathymetry and by wave interactions with currents. The model includes a wave breaking model based on water depth and wave steepness. Model output includes significant wave height (H_s), peak wave period (T_p), and mean wave direction ($\overline{\theta}$).

STWAVE is an efficient program that requires minimal computing resources to run well. The model is implemented using a finite-difference scheme on a regular Cartesian grid (grid increments in the *x* and *y* directions are equal). During a model run, the solution is computed starting from the offshore open boundary and is propagated onshore in a single pass of the model domain. As such, STWAVE can propagate waves only in directions within the ±87.5° half plane. A benefit of using this single pass approach is that it uses minimal computer memory because the only memory-resident spectral data are for two grid columns. Accordingly, changing wave spectra across each grid column are computed using information from the previous grid column only.

STWAVE is based on a form of the wave action balance equation. The wave action density spectrum, which includes the effects of currents, is conserved along wave rays. In the absence of currents, wave rays correspond to wave orthogonals, and the action density spectrum is equivalent to the wave energy density spectrum. A diagram showing the relationship between wave orthogonal, wave ray, and current directions is shown in **Figure 5.23**. The governing equation of wave transformation, using the action balance spectrum, in tensor notation is written as follows (Smith et al., 1999):

$$\left(C_{ga}\right)_i \frac{\partial}{\partial x_i} \frac{C_a C_{ga} \cos(\mu - \alpha) E}{\omega_r} = \sum \frac{S}{\omega_r} \tag{1}$$

where

E = $E(f,\theta)$ wave energy density spectrum;
S = energy source and sink terms (e.g., white capping, breaking, wind input);
α = wave orthogonal direction;
μ = wave ray direction (direction of energy propagation);
ω_r = relative angular frequency ($2\pi f_r$); and
C_a = absolute wave celerity; and
C_{ga} = absolute group celerity.

The breaking model in STWAVE is based on a form of the Miche criterion as discussed by Battjes and Janssen (1978). It sets a maximum limit on the zero-moment wave height (H_{mo}), the wave height based on the distribution of energy in the wave spectrum. The formulation of this model is

$$H_{mo(max)} = 0.1L \tanh(kd) \tag{2}$$

where L is the wavelength, k is the wave number ($k = 2\pi/L$), and d is the depth at the point where the breaking limit is being evaluated. This equation is used together with a simpler breaking model, which was used alone in earlier versions of STWAVE, where the maximum H_{mo} wave height is always expressed as a constant ratio of water depth.

$$H_{mo(max)} = 0.64\ d \tag{3}$$

An advantage of using Equation 2 over Equation 3 is that it accounts for increased wave breaking resulting from wave steepening caused by wave-current interactions. Once model wave heights exceed $H_{mo(max)}$, STWAVE uses a simple method to reduce the energy spectrum to set the value of $H_{mo} = H_{mo(max)}$. Energy at each frequency and direction is reduced by the same percentage. As a result, nonlinear transfers of energy to high frequencies during breaking are not included in STWAVE.

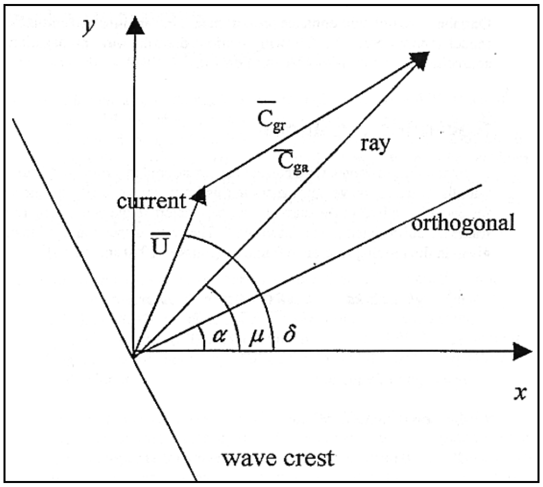


Figure 5.23. Wave and current vectors used in STWAVE. Subscript *a* denotes values in the *absolute* frame of reference, and subscript *r* denotes values in the *relative* frame of reference (with currents).

5.2.4.1 Model Domain and Bathymetry

Wave modeling consisted of a single model grid (100-m x 100-m grid cells) that included all three shoals of interest (**Table 5.3**). The limits of the grid (**Figure 5.24**) were chosen so that the offshore boundary coincided with the longitude for WIS Station 161, the station chosen to supply boundary conditions for wave modeling runs. Lateral extents of the coarse grid were selected far enough away from the shoal to ensure that the model domain was free from any edge effects present in the solution.

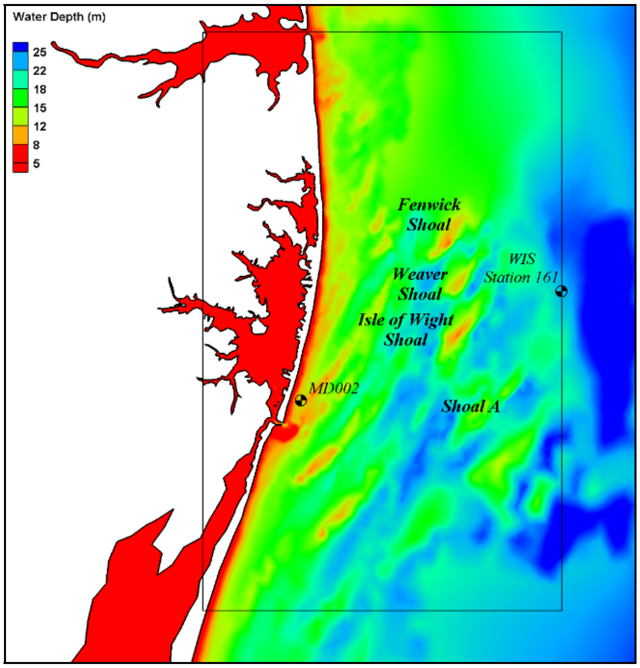


Figure 5.24. STWAVE bathymetry and model grid domain. The location of WIS Station 161 is shown as a circle on the eastern boundary.

Table 5.3. Dimensions for the wave grid.

Cell Size	Grid Dimensions	Number of Water Cells	Typical Run Time (19 Wave Cases)
100 m x 100 m	233 rows x 144 columns	25,439	~28 minutes

Bathymetry data were gathered from several sources and combined to provide a single data set covering the entire study area. Offshore bathymetry is composed of data collected in the 1970's and digitized from National Ocean Service (NOS) hydrographic surveys (H-sheets). High density survey data of each shoal were provided by the USACE Baltimore District to supplement the existing NOS data set. These survey data were collected in November 2002 as part of an offshore sand resources study of the Atlantic Coast of Maryland (USACE, 2008).

5.2.4.2 Boundary Conditions

STWAVE input spectra were developed using a numerical routine that recreates a 2-D spectrum from whichever individual wave condition in the WIS record is requested. The program computes the frequency and directional spread of a wave energy spectrum based on significant wave parameters (i.e., wave height, peak period, and peak direction) and wind speed (Goda, 1985). The frequency spectrum $S(f)$ is computed using the relationship

$$S(f) = 0.257 H_{1/3}^2 T_{1/3} (T_{1/3} f)^{-5} \exp\left[-1.03 (T_{1/3} f)^{-4}\right] \tag{4}$$

known as the Bretschneider-Mitsuyasu spectrum, where $H_{1/3}$ is the significant wave height, f is the discrete frequency where $S(f)$ is evaluated, and $T_{1/3}$ is the significant period, estimated from the peak wave frequency (f_p) by

$$T_{1/3} = 1/\left(1.05 f_p\right) \tag{5}$$

To compute the two-dimensional energy spectrum, a directional spreading function $G(f,\theta)$ must be applied to the frequency spectrum such that

$$S(f,\theta) = S(f) G(f,\theta) \tag{6}$$

In this method, the directional spreading function is computed using the relationship

$$G(f,\theta) = G_o \cos^{2s}\left(\frac{\theta}{2}\right) \tag{7}$$

where s is a spreading parameter related to wind speed and frequency, θ is the azimuth angle relative to the principal direction of wave travel, and G_o is a constant dependent on θ and s. The spreading parameter s is evaluated using the expression

$$s = \begin{cases} s_{\max} \cdot (f / f_p)^5 : f \le f_p \\ s_{\max} \cdot (f / f_p)^{-2.5} : f \ge f_p \end{cases} \tag{8}$$

where $s_{\max} = 11.5(2\pi f_p U / g)^{-2.5}$. Wind speed U is therefore used to control the directional spread of the spectrum by increasing the directional spread with increasing wind speed (g is the acceleration of gravity). Finally, the constant G_o is computed by evaluating the integral.

$$G_o = \left[\int_{\theta_{\min}}^{\theta_{\max}} \cos^{2s}\left(\frac{\theta}{2}\right) d\theta \right]^{-1} \tag{9}$$

The result is a wave energy spectrum that is based on parameters from the WIS record, and that distributes spectral energy based on wave peak frequency and wind speed. An example of a 2-D spectrum generated by this method is presented in **Figure 5.25**.

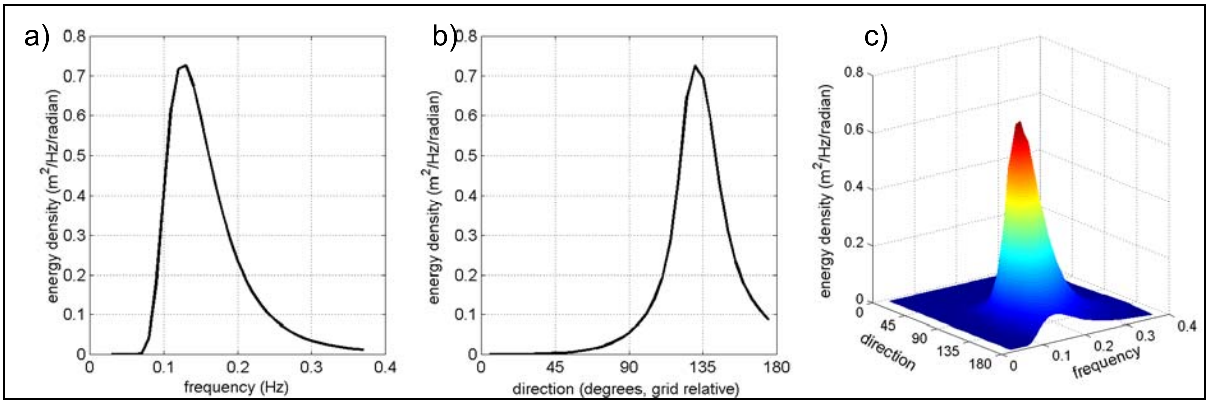


Figure 5.25. STWAVE input spectrum developed using WIS 20-year hindcast data with the Goda (1985) method of computing frequency and direction spectrum. Plots show a) frequency distribution of energy at peak direction, b) directional distribution of energy at peak frequency, and c) surface plot of energy spectrum (H_{mo} = 0.9 m, θ_{mean} = 130°).

5.2.4.3 Nearshore Wave Prediction Versus Gage Measurements

Before proceeding with model simulations under various dredging scenarios, wave model simulations were compared with USACE wave gage measurements collected off Ocean City in 9-m water depth (USACE Gage MD002; **Figure 5.15**). The purpose of this effort was to test the reliability of STWAVE at predicting wave propagation in the project area. Because most wave energy in this area is from the northeast, WIS and USACE wave gage records were examined to identify a storm event from the northeast. A storm in October 1997 was chosen where the inshore wave heights exceeded 2 m and the wind was from the northeast. For this same time period, WIS results from Station 161 were used as input for STWAVE, and model results were compared to gage data.

It is unrealistic to expect an exact match of wave conditions at the wave gage location because input from WIS is itself modeled data. But with that caveat, there is still value in comparing STWAVE results to field data as plotted in **Figure 5.26**. Simulated (STWAVE; triangles) and measured (MD002; squares) wave heights at the location of the USACE nearshore wave gage were compared to assess the reliability of propagating simulated WIS results across the study area. **Figure 5.26** illustrates wave height differences (x) taken as the absolute value of the difference between the recorded wave height and the STWAVE prediction at the gage location.

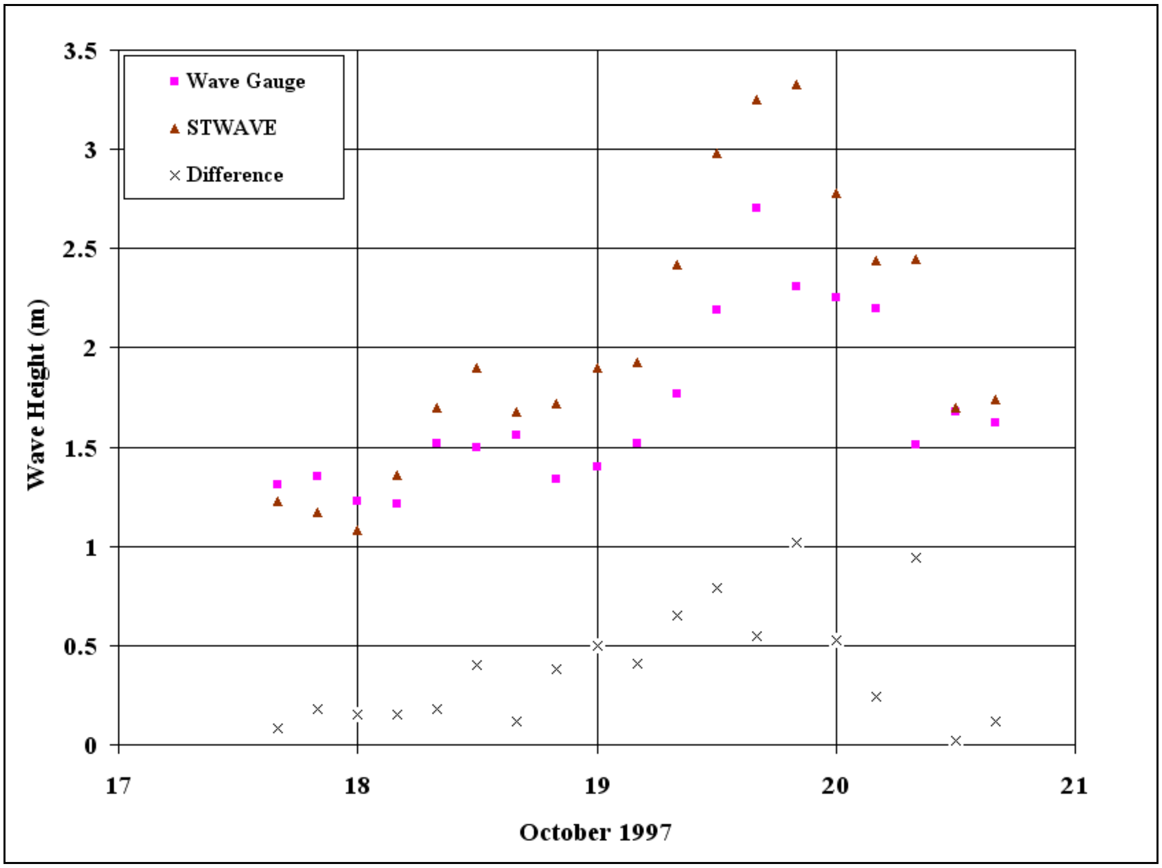


Figure 5.26. Wave height values from USACE nearshore gage MD002 during the 1997 storm. STWAVE results using WIS Station 161 input and wave measurements for the nearshore gage are plotted for comparison. The difference between simulated wave heights and measurements documents maximum difference during the peak of the storm.

The overall signature of storm intensity is recreated well, indicating that WIS data generally capture the timing of a storm event. For the first 24 hours, little difference exists between wave height simulations and gage measurements. This close agreement suggests that the wave model is accurately simulating wave propagation across the ridges and swales within the model grid. STWAVE results indicate a noticeable departure from field data during the height of the storm. It is difficult to say if this is a result of model uncertainty or the trend of WIS data over-predicting wave heights at the peak of storms, as was discussed above when comparing WIS data to NDBC Buoy 44009.

Following the peak of the storm, agreement between model results and measured wave heights becomes more reliable. Over the course of the 3-day storm, STWAVE results in the nearshore echo of the trend seen in field data and demonstrate an adequate agreement with specific wave heights from the wave gage.

Throughout the storm period, wave direction appears biased 5º to 10º to the north of field measurements. This discrepancy is likely the result of resolution deficiency in nearshore bathymetry and possibly coarseness of the wave grid. During model grid construction, detailed bathymetry was used for shoals in the study area, but in the nearshore, bathymetric data were relatively sparse. Without detailed representation of shoals closer to shore, and without increased grid spacing, wave modeling is not able to accurately recreate refraction and shoaling closer to shore. As such, differences between the model results and the field observations are recorded.

5.2.4.4 Wave Model Results

Overall, the study is focused well offshore of the region where the wave gage was deployed, and the discussion that follows focuses on wave model results for northeast and easterly storms in the area of Weaver Shoal, Isle of Wight Shoal, and Shoal A. **Figure 5.27** illustrates bathymetry within the study area over which waves were propagated to provide a reference for evaluating wave modeling results.

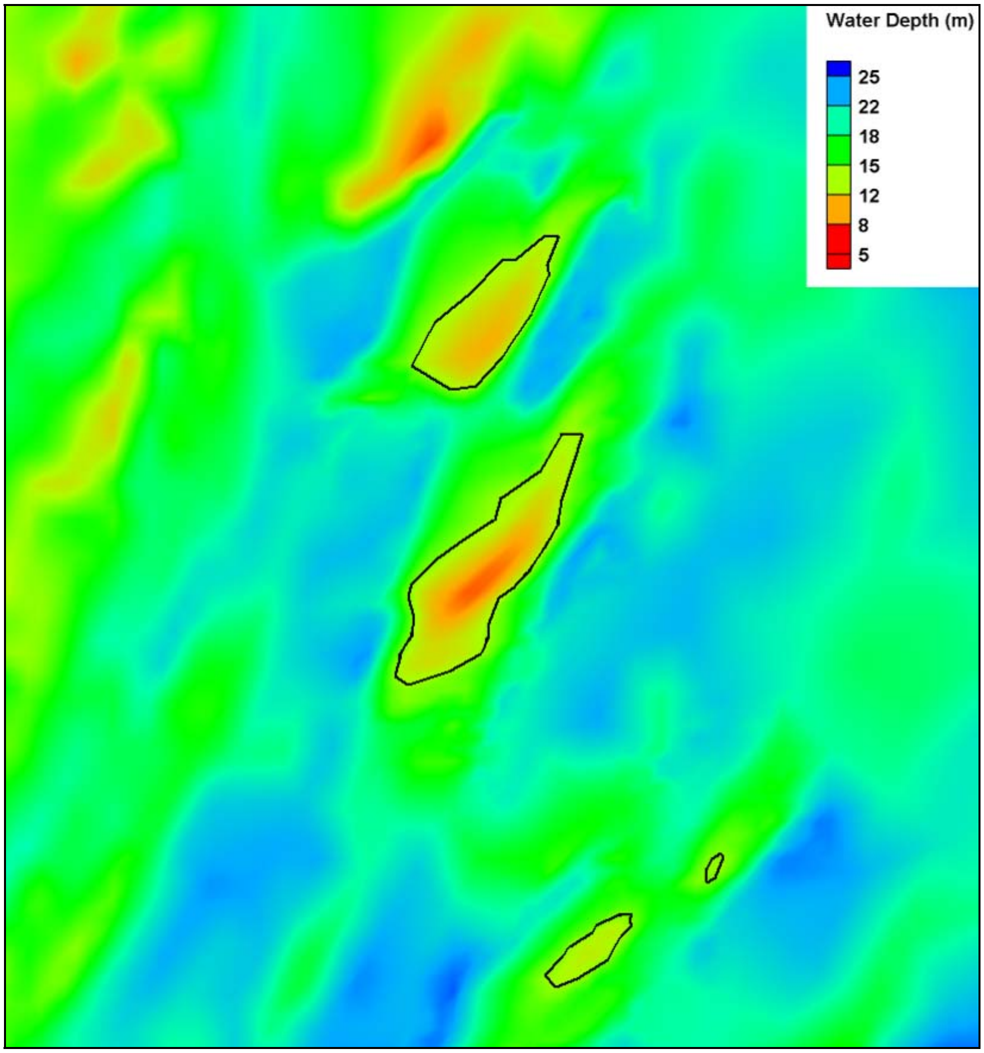


Figure 5.27. Wave model bathymetry for the study area. The 12-m contour is outlined on each shoal as a reference.

Figure 5.28 shows one time-step of the 3-day storm event for the (a) northeast case and (b) east case. For the northeast case, incident wave heights are on the order of 5 m. As waves propagate shoreward from the east, uniform wave heights and directions observed at the boundary are replaced by varying wave heights and directions as wave energy is redistributed by interacting with shoal bathymetry. Between Fenwick, Weaver, and Isle of Wight shoals, there is a repeated pattern of increased wave heights in the area of shoals and a decrease in wave height at low regions between the shoals. Waves encountering shoals from deep water will experience shoaling, with an accompanying increase in wave height and possibly breaking. Furthermore, wave energy is focused or dispersed due to refraction over the shoals. This wave focusing is especially apparent in **Figure 5.28(a)**, where waves from the northeast are traveling parallel to bathymetric features oriented to the northeast. As waves approach the shoals, they are influenced by bathymetry long before they encounter the shoal crest (denoted by the 12-m depth contour). Weaver and Isle of Wight shoals have regions of shallow bathymetry immediately to the northeast of their crests (see **Figure 5.27**). As waves from the northeast approach shoal crests, wave vectors illustrate energy being focused on the north side of each shoal. Accompanying this refraction pattern and subsequent increase in wave height is a decrease in wave height immediately to the south of the shoal.

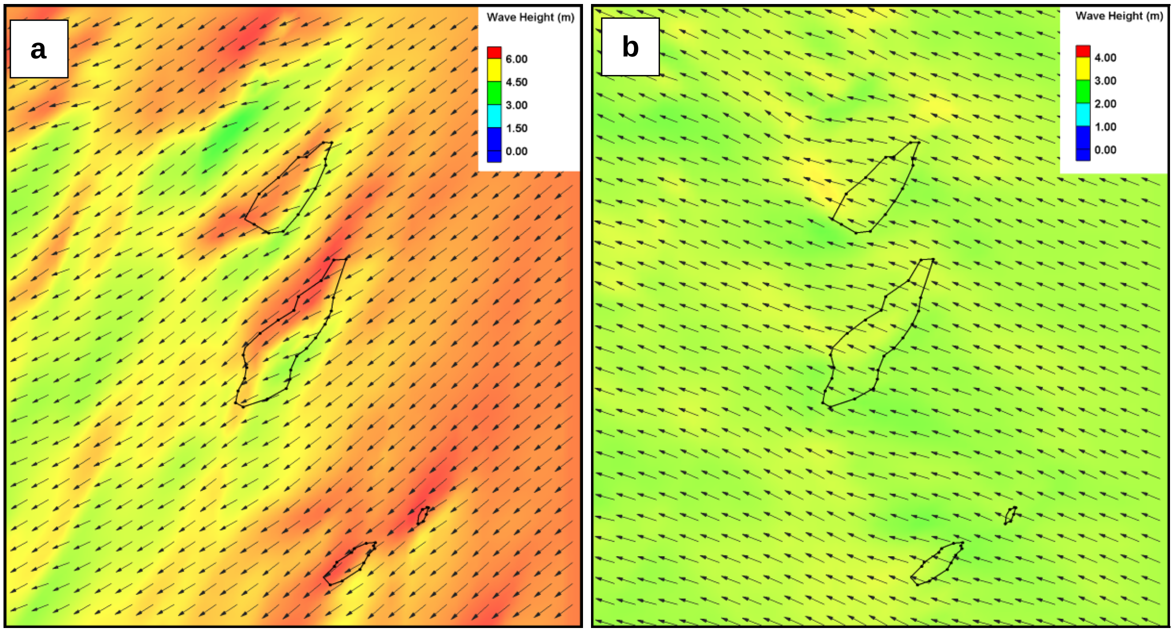


Figure 5.28. Wave model results in Hour 40 of the storms with waves incident from a) the northeast and b) the east. Note that the color scale range is different for the two wave conditions.

Figure 5.28(b) illustrates wave results for a single time during the storm from the east. For this particular image, waves are incident slightly south of east with wave heights at the boundary of 2.6 m. It is immediately apparent that the model results for this run are significantly different from those of the northeast case. The most striking difference is the relative uniformity of wave height across the entire domain for this wave condition. There are none of the areas of banded wave heights that were seen in the previous scenario. There are two primary reasons for this difference. The first is that the wave heights in this scenario are relatively small and less affected by shoal bathymetry. Water depths across the shallowest part of Isle of Wight Shoal are on the order of 7 m, and these 2.5-m waves pass across the shoals relatively unchanged. The second reason for the difference in wave results is that waves are incident from a direction perpendicular to shoal orientation. From this direction, bathymetry changes are relatively sharp, and there is an expected increase in wave heights across the crests of the shoals. Some refraction is evident as the waves pass over the crests of the shoals, but without long stretches where waves are running parallel to a ridge and trough, there is not the opportunity for the strong wave focusing observed in the northeast storm.

5.2.5 Nearshore Sedimentation and Borrow Site Infilling

The primary purpose for wave transformation modeling in this study is to predict wave shear stress and momentum so morphology change calculations can be performed with input from waves and currents under imposed storm conditions. WIS information was examined to identify the largest storm event from the northeast between 1980 and 1999 as one wave condition for morphologic change modeling. An event from mid-October 1984 was chosen, where waves at WIS 161 were from the northeast and exceeded 6 m at the peak of the storm. WIS information was also examined to find a large storm from the east to observe the impact of wave direction on morphologic change simulations. The event chosen took place in late September 1992, when wave heights briefly exceeded 5 m. In both cases, wave information was input from the record every 4 hours for 72 hours. Including an initial wave case at time zero, this approach yielded 19 wave height/direction pairings for each scenario.

By combining wave and hydrodynamic modeling results with appropriate nearshore sediment transport formulae, seafloor change simulations were conducted to predict natural and dredging-induced responses to incident coastal processes. It was anticipated that numerical simulations would shed light on the most likely pathways for sediment movement, as well as provide some idea of the relative magnitude of change under differing wave and dredging conditions. The response of each shoal to various dredging scenarios is of primary interest. This component of the modeling effort was concerned with morphology response of offshore shoals to various sand mining scenarios.

CMS-M2D – CMS-M2D is a 2-D, depth-integrated, finite-difference hydrodynamic model. It also has the option of including morphology change estimates through the use of a sediment continuity equation for updating changes in bathymetry. Full coupling with an external wave model (STWAVE in this case) is possible, with the wave model providing radiation and shear stresses to CMS-M2D. In return, the hydrodynamic and morphology changes are passed back to the wave model.

5.2.5.1 Model Domain

Limits of the model domain were chosen to encompass shoals and adjacent environments to provide a well-determined boundary for hydrodynamics. It is best practice for the hydrodynamic grid to lie completely within the wave grid for the coupled STWAVE and CMS-M2D simulations. This prevents the need for CMS-M2D to extrapolate radiation and shear stresses past the boundaries of the wave model solution. The final CMS-M2D model domain was developed with these concerns in mind (**Figure 5.29**). Many attempts were made to develop a model solution using four ocean boundaries to reduce computation time. Ultimately, this approach was abandoned in favor of the larger domain, which was widened to include a shoreline boundary on the west.

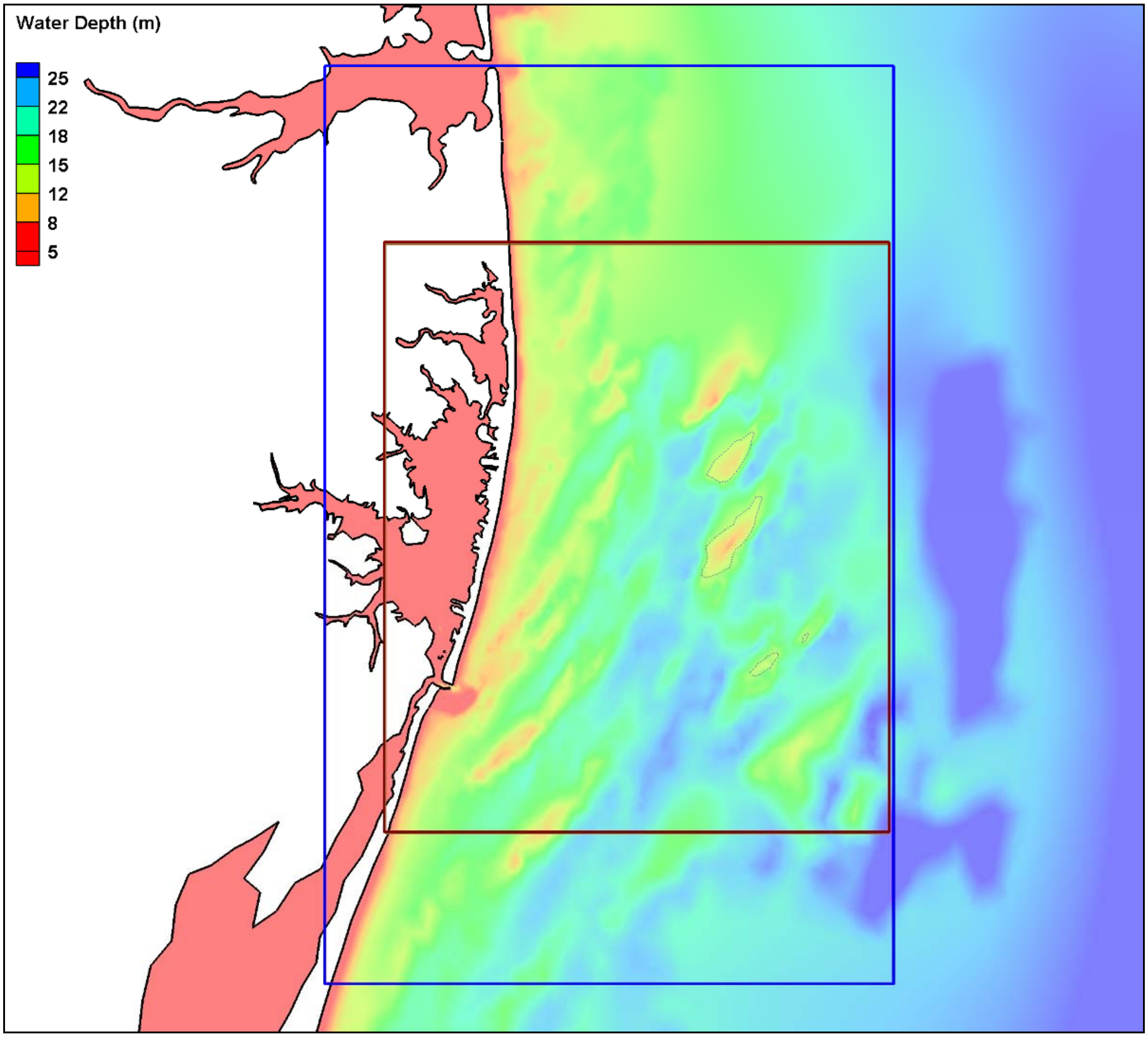


Figure 5.29. CMS-M2D model domain is marked by the brown rectangle. The navy rectangle illustrates the limits of the STWAVE model grid for comparison.

One benefit of the CMS-M2D model is its ability to incorporate variable cell sizes, so the model can provide fine resolution across the shoals where greatest change is expected, and grid cells away from the shoals have a wider spacing. This flexibility allows for optimization between proper grid resolution and run time efficiency. Grid cells in the CMS-M2D model vary between 60-m spacing across much of the shoals, expanding to 250-m spacing at the corners of the domain. **Figure 5.30** shows the finished grid with variable spacing.

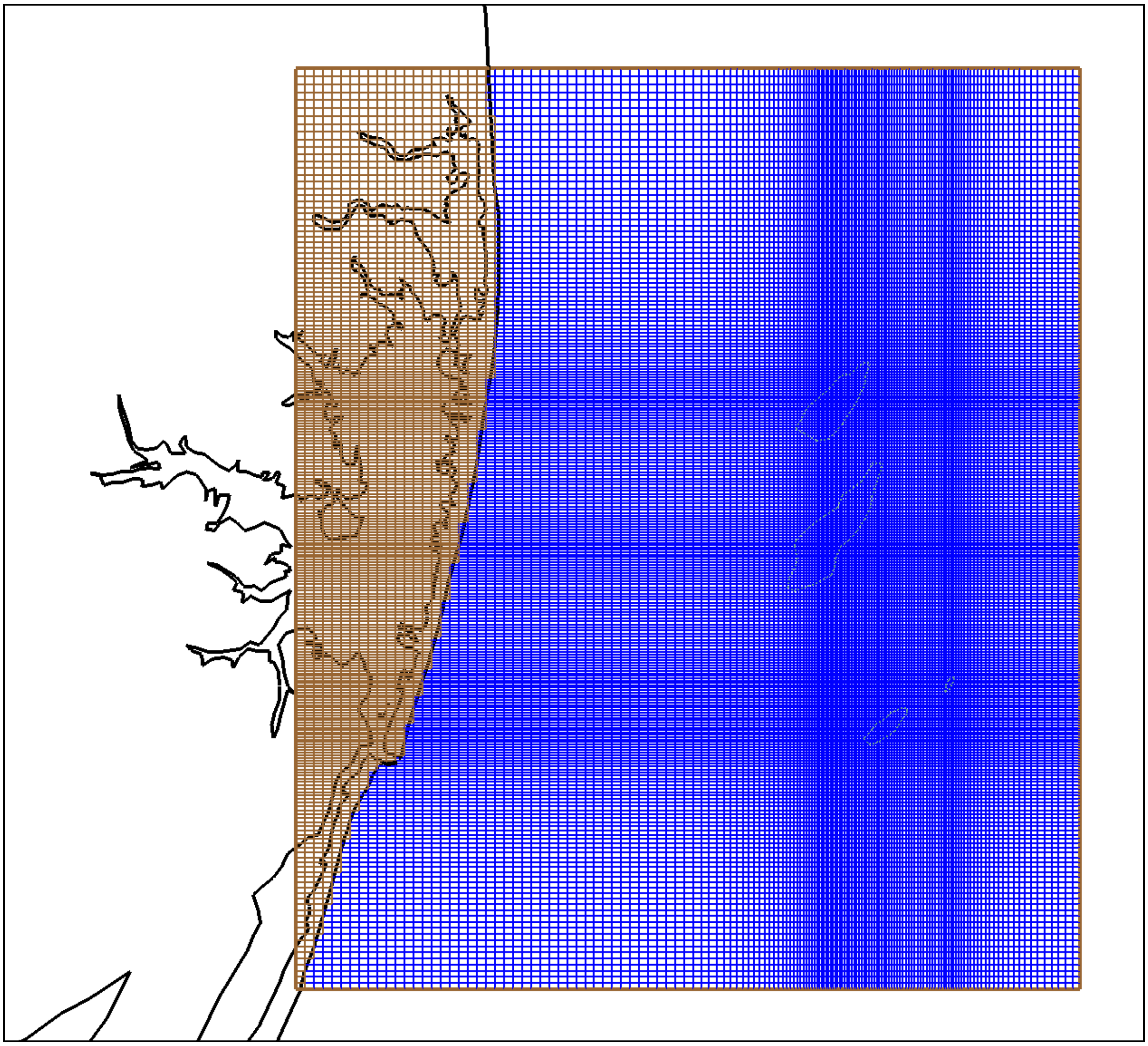


Figure 5.30. CMS-M2D model grid showing the variable cell spacing.

5.2.5.2 Dredging Scenarios

As discussed in **Section 5.1.2**, four scenarios were chosen to examine sediment transport patterns in response to incident coastal processes, including baseline, dredging the crest of a shoal to a specified bathymetry contour, dredging the leading edge of the shoal, and dredging a striped pattern over the shoal crest to facilitate recruitment of benthic invertebrates. For each scenario, the lateral extents of dredging were determined based on the location of desirable sand on each shoal (USACE, 2008). If a specific scenario would call for dredging in an area with poor sand quality, this scenario was not evaluated for the shoal in question. For example, sand on the crest of Shoal A was not deemed acceptable by the USACE (2008), so dredging on the shoal crest (trailing edge) was not imposed within the model domain for this site. **Table 5.4** illustrates the final configuration of modeling runs within the project area.

Table 5.4. Selected dredging scenarios.

Scenarios	Weaver Shoal	Isle of Wight Shoal	Shoal A
Baseline (No Action)	x	x	x
Crest Polygon	x	x	x
Leading/Trailing Edge	x	x	---
Striped Pattern	x	x	x
x = simulated scenario; --- = no simulated extraction			

5.2.5.3 Boundary Conditions

The hydrodynamic solution from the ADCIRC simulation was used to provide a time series of water levels along each open boundary. The 3-day period from 6-9 October 1991 was used to drive hydrodynamics in the CMS-M2D simulations. This period was selected because it represented a typical tidal range (~1 m) during a time of low freshwater runoff. This simulation served to recreate average tidal conditions.

For each of the scenarios in **Table 5.4**, two separate wave conditions were imposed. The first was a severe storm from the northeast with significant wave heights approaching 6 m at WIS Station 161. The second wave condition was an easterly storm with wave heights approaching 5 m at WIS Station 161. As modeling scenarios were being finalized, a storm from the southeast with maximum wave heights of 3 m was also evaluated. The initial results indicated these smaller wave heights were insufficient to produce any significant morphology change on the shoals. As a result, the southeast storm condition was replaced by the more energetic easterly condition.

5.2.5.4 Model Setup

With boundary conditions assigned, the remainder of model setup was concerned with properly choosing variables relevant to morphology predictions, as well as the coupling between STWAVE and CMS-M2D. A summary of model variables is provided in **Table 5.5**. The advection-diffusion transport scheme was chosen because it is the only formulation that accounts for suspended load and bed load transport separately. The role of suspended sediment is especially important in these dredging scenarios, because it is primarily responsible for infilling of the interior of dredged areas. Other "total load" transport formulations available in CMS-M2D would not be as robust in this regard.

Table 5.5. Values for CMS-M2D model variables.

Variable	Setting
Hydrodynamic time step	3 seconds
Transport Rate time step	30 seconds
Morphologic time step	30 minutes
Sediment transport formulation	Advection-diffusion
Mean grain size	0.4 mm
Interface with STWAVE every	4 hours

5.2.5.5 Morphological Model Results

While morphological modeling does provide specific values of bottom change for individual storm conditions, without data to calibrate these results, quantitative estimates of change should be treated with caution. The true value of morphological modeling is not in the specific values of bottom change, but rather how the results differ from each other as starting bathymetry and wave conditions are varied. It is relative change between scenarios that is most reliable and not the absolute magnitude of specific change calculations.

Baseline (No Action)

Initial model simulations examined predicted change under storm conditions for existing bathymetry, with no dredging performed. This scenario is labeled Baseline in **Table 5.4**. Documenting results from these runs provided a basis for comparing modeled dredging scenarios. Although Fenwick Shoal is shown at the northern extent of the model domain, the shoal is not included in any of the dredging scenarios.

Figure 5.31(a) illustrates initial bathymetry for the shoal complex. **Figure 5.31(b)** documents bottom change predicted under northeast storm conditions. As expected, a general trend of erosion (yellow and red colors) is illustrated along northern portions of the shoal with deposition (green and blue colors) to the south. Because wave energy is incident from the northeast, sand is suspended along the northern section of the shoal crest and pushed to the leading edge, where is it deposited. This pattern is seen most clearly at Isle of Wight Shoal, where there is a clear area of erosion on the northern half of the crest and then subsequent deposition in three bars along the southern face of the shoal. A similar trend is seen on Shoal A, with distinct patterns of change on both the smaller subshoals. Weaver Shoal indicates deposition along the leading edge but no clear area of erosion, suggesting that the sediment depositing along the front edge is an accumulation of sand from a wider area of the shoal to the north, as opposed to a specific location.

It is interesting to note the relative magnitude of change observed between the shoals. Isle of Wight (and Fenwick Shoal at the far north) exhibit(s) well-defined areas of change, as should be expected from the shallowest areas of the study site. Both have depths of ~7 m along the shoal crest. Weaver Shoal is situated between these shoals, reaching a minimum depth of ~9 m at the crest. Sheltered to some extent by Fenwick Shoal and the wide expanse of deeper shoals to the north, relatively little seafloor change is predicted. Shoal A, at the southern extent of the study area, is relatively isolated, and despite being the deepest of the shoals (having a minimum crest depth of ~11 m), change patterns are still observed.

Figure 5.31(c) reveals that with a significant storm from the east, there is relatively little bottom change predicted. It should be noted that while change predicted for the northeast storm shown in (b) is on the order of 0.1 m, change from the easterly event in (c) is on the order of 0.01 m as denoted by the color scale bars. Although there is an order of magnitude difference in bottom change predictions, these results are still useful to illustrate how change patterns differ from the northeast wave case. They also provide reference for evaluating change predicted for the dredging scenarios.

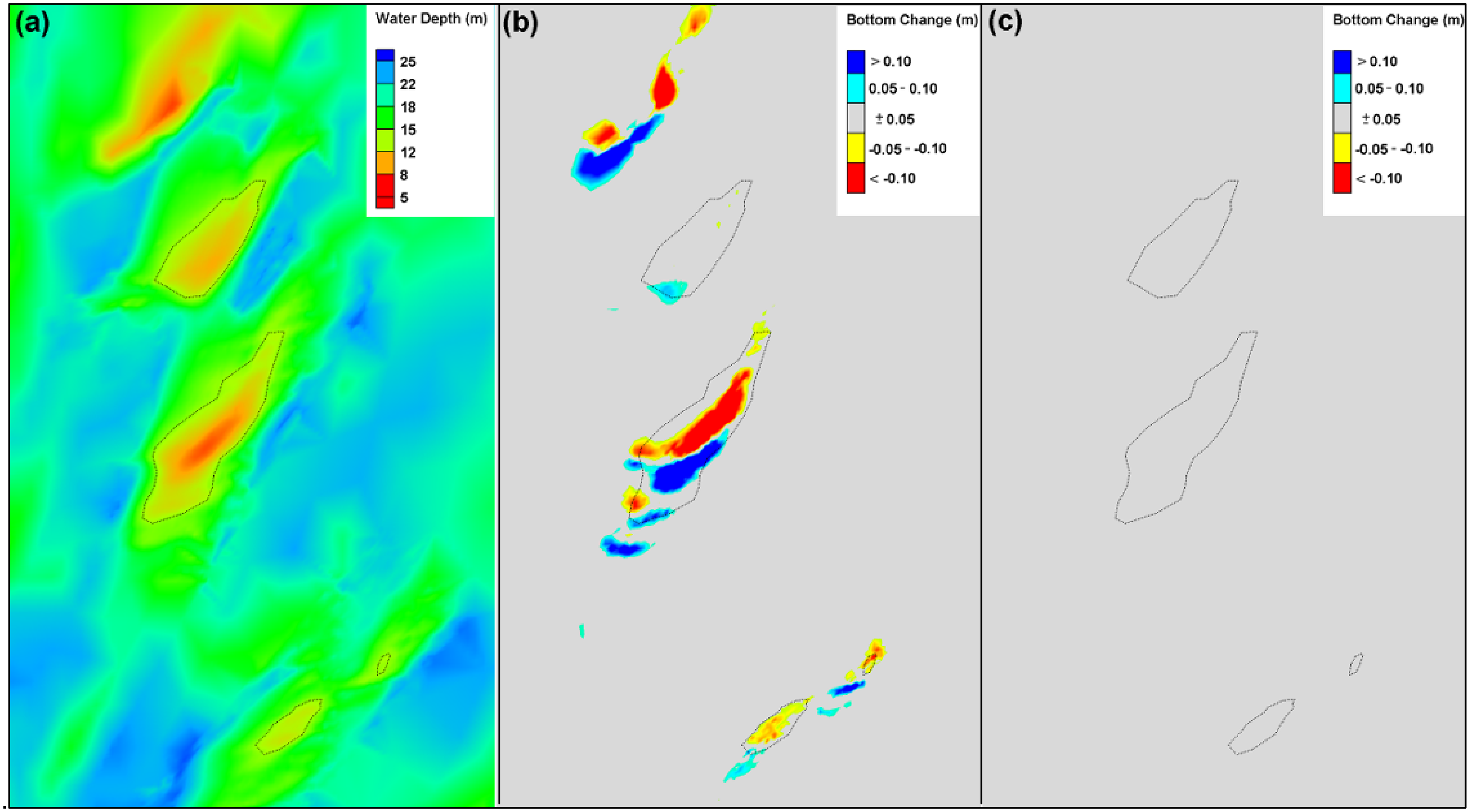


Figure 5.31. CMS-M2D model results for existing conditions showing a) bathymetry at the start of the model run, b) bottom change calculated for the northeasterly storm condition, and c) bottom change for the easterly storm condition. For reference, all plots show the 12-m depth contour for Weaver, Isle of Wight, and Shoal A.

Isle of Wight Shoal provides the strongest signature of change with erosion along the eastern face of the shoal where wave energy first impacts the shoal, and deposition on the westerly face as water depths decrease. Weaver Shoal displays a small area of erosion on the easterly face but no corresponding area of deposition, suggesting that sand is distributed widely across the rest of the feature. Shoal A shows no appreciable bottom change at all, indicating that shoal depth limits the influence of these wave conditions.

Figure 5.32 illustrates average transport vectors for the Baseline scenario during the northeast storm condition. This plot is a snapshot of a single time step extracted from the 3-day simulation. The figure illustrates magnitude (color) and direction (arrow) of average sediment transport (bed load and suspended load) calculated by CMS-M2D. There is a clear trend of transport from the northeast to the southwest for each of the shoals, which matches the direction of wave propagation. This trend in transport serves as further confirmation that sand transport and shoal morphology on short time scales is dominated by wave forcing. Sand transport across Isle of Wight Shoal (and Fenwick Shoal) is greater than that observed at Weaver Shoal and Shoal A, a trend consistent with morphology change results. For all shoals, an increase in transport rate is documented as waves approach the shoal crest. Maximum transport is attained across the crest, and magnitudes decrease shoreward of the shoals. The same general trend was documented for each of the following dredging scenarios, regardless of specific geometric characteristics for each scenario. As a result, additional transport plots for each scenario are not included below.

Crest Polygon

The shoal crest dredging scenario consisted of a single polygon dredged from each of the shoals. The crests of Weaver and Isle of Wight shoals were dredged, while a section along the northwest face of Shoal A was dredged (**Figure 5.33[a]**). Sediment sampled at the crest of Shoal A was eliminated from consideration by USACE (2008), but sand on the trailing edge to the northwest was deemed acceptable.

Figure 5.33 indicates that during a strong storm from the northeast, Weaver Shoal will experience sand transport from the northeast and deposition adjacent to the edge of the "dredged" area. The northwest margin of the excavation site also illustrates some deposition. In total, 9,000 m^3 of sand were deposited within the boundaries of the dredging area. The absence of deposition further into the center of the dredged area can be understood as an absence of sand transport into the depression. All sand moved from the northeast face of the shoal is deposited immediately upon transport into the "dredged" region of the shoal. It should be expected that over time, the center of the dredged area would start to fill, with the southern extent of the "dredged" area being the last region to fill. There is still some deposition along the leading edge of the shoal, as was observed under the Baseline scenario discussed above.

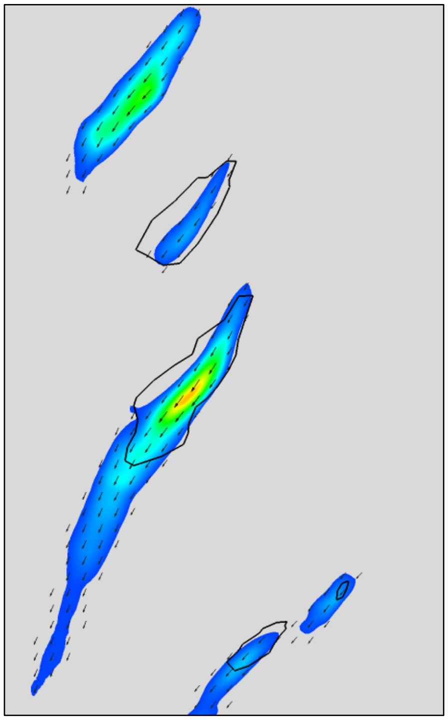


Figure 5.32. CMS-M2D average transport vectors for the Baseline scenario.

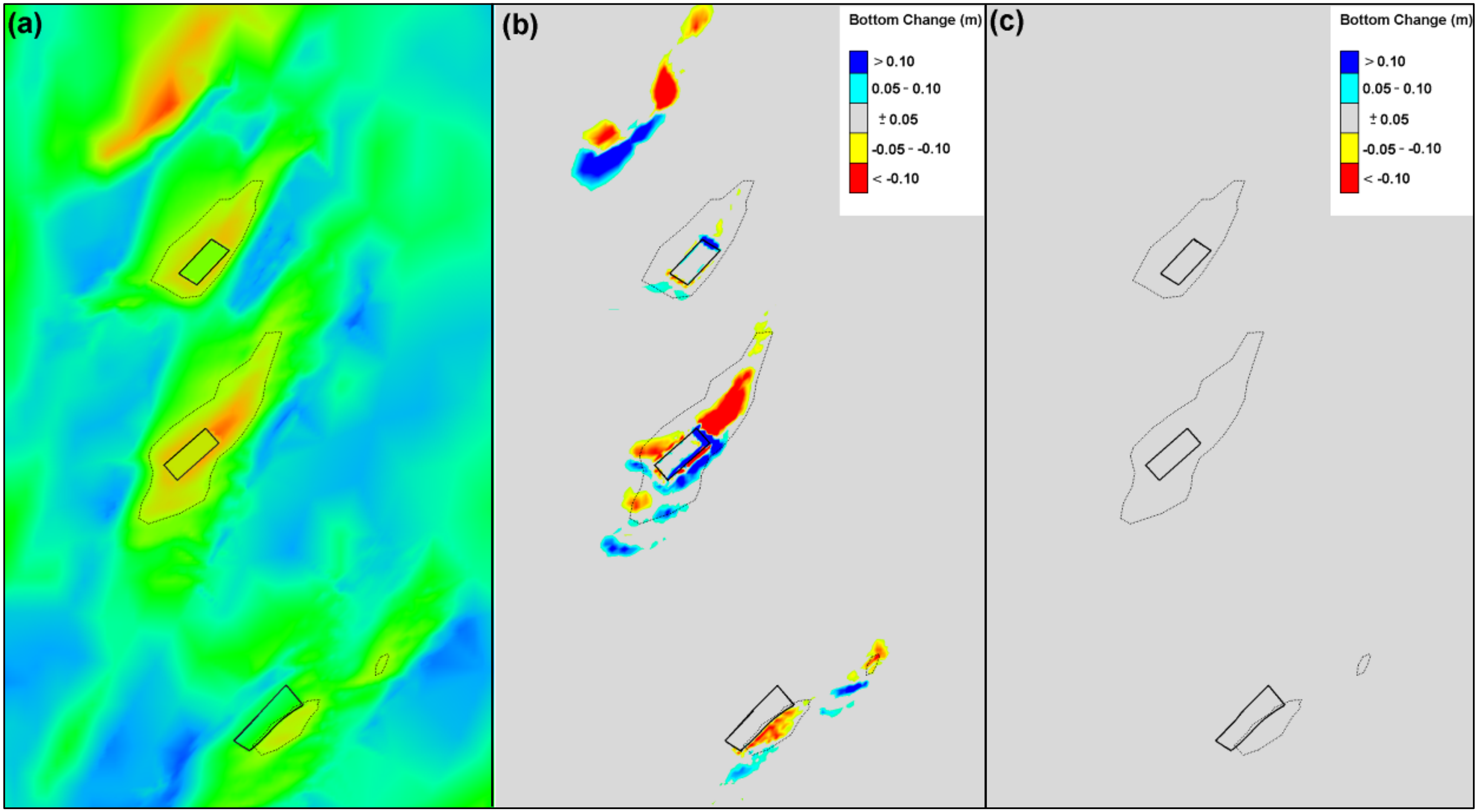


Figure 5.33. CMS-M2D model results for numerically excavated sand from each of the shoals for the Crest Polygon scenario, showing a) bathymetry at the start of model run, b) the bottom change calculated for the northeasterly storm condition, and c) bottom change from the easterly storm condition. For reference, all plots show the 12-m depth contour for Weaver, Isle of Wight, and Shoal A. The extents of the “dredging” areas are outlined in black.

In contrast to Weaver Shoal, there is significantly more sand eroded from the northeast face of Isle of Wight Shoal, and subsequently, a larger area of sediment deposition is observed within the "dredged" area. The same general pattern is observed where there is greater infilling at the northeast extent of the "dredged" region, but the magnitude and spatial extent of deposition is much larger. Total sediment deposition within the impacted area is about 40,000 m^3.

Shoal A, to the south, shows little change in morphology compared with the Baseline scenario. The "dredged" region along the northwest face of the shoal exhibits no observable infilling, while similar modest changes are observed at the shoal crest. If there is any sand moving along Shoal A, it is not coming into contact with the dredged region, and hence, there is no deposition. Aside from the very top of the shoal crest, again we see that water depths are too deep to result in significant sediment mobilization along the trailing edge of the shoal.

Figure 5.33(c) shows virtually no morphology change for storm conditions approaching from the east. Water depths are too great at Weaver Shoal and Shoal A for any appreciable sediment movement, and Isle of Wight Shoal records only the smallest amount of change.

Leading/Trailing Edge

The second numerical excavation scenario consisted of dredging the leading edge of Weaver Shoal and the trailing edge of Isle of Wight Shoal. There is no "dredging" depicted on Shoal A for this scenario.

Under a significant storm from the northeast, the numerically excavated region on the leading edge of Weaver Shoal illustrates infilling (**Figure 5.34**). Greatest deposition was observed along the southwest face of the shoal, with a thin band of accretion also appearing along the southeast margin of the "dredged" area. This pattern is similar to that observed in other excavation scenarios, with the exception being that most deposition is occurring closer to the crest of the shoal as a result of the dredged region extending toward the crest. Approximately 26,000 m^3 of sand are deposited within the "dredged" area on the front of the shoal.

At Isle of Wight Shoal, the northwest face of the shoal contained quality beach sand that was numerically removed to evaluate sediment transport changes resulting from sand dredging. There are small areas of accretion along the edges of the dredged area closest to the crest. However, most of the sediment moved from the crest is deposited along the southeast face of the shoal. There is little forcing during this event to move suspended sediment over the crest to the north and into the "dredged" area. Only 8,000 m^3 of sand returned to the "dredged" area during the simulation.

Again, for the case of the easterly storm shown in **Figure 5.34(c)**, there is no significant change in shoal morphology. The small amount of change illustrated for Isle of Wight Shoal indicates sand moving from east to west across the crest of the shoal, perhaps settling partly within the eastern edge of the "dredged" region.

Striped Pattern

The third numerical excavation scenario consisted of trenches dredged across the same regions of the shoal as the Crest Polygon scenario. The crests of Weaver and Isle of Wight shoals and the northwest face of Shoal A were "dredged" in a striped pattern. The striping consisted of swaths of sand numerically excavated 3-m deep, with a spacing of 50 m over a distance of about 1 to 2 km.

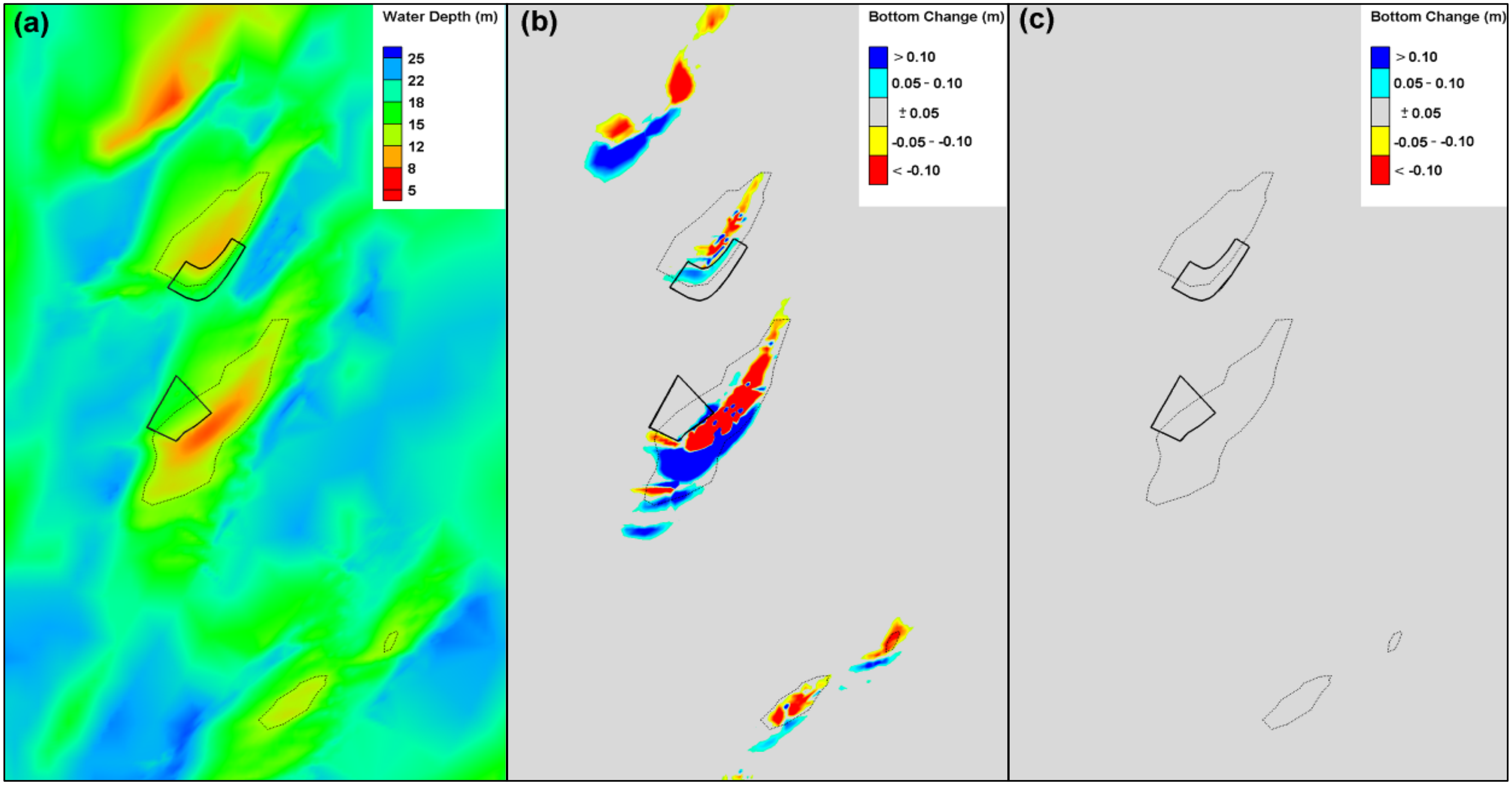


Figure 5.34. CMS-M2D model results for numerically excavated sand from the leading edge of Weaver Shoal and the trailing edge of Isle of Wight Shoal, showing a) bathymetry at the start of model run, b) bottom change calculated for the northeast storm condition, and c) bottom change from the easterly storm condition. For reference, all plots show the 12-m depth contour for Weaver, Isle of Wight, and Shoal A. The extents of the “dredging” areas are outlined in black.

Figure 5.35 illustrates morphology change for the striped excavation scenario on shoal crests. For each of the shoals, excavated troughs began to fill while the undisturbed regions between the troughs were eroding. For Weaver and Isle of Wight shoals, there is a similar pattern of erosion and deposition to that identified for Crest Polygon "dredging," where greatest deposition occurs from northeast to southwest. Furthermore, there is persistent deposition throughout the entire "dredged" area. Deposition in the center and southern portions of the excavated area is a result of redistribution of sand from undisturbed areas between the troughs into adjacent low areas. This pattern is seen again within the area "dredged" in Shoal A, although the lowest areas of striping along the northwest face remain unchanged.

For the Striped Pattern scenario, volume loss (from the eroding ridges) and volume gain (deposition in troughs) is measured for each shoal. At Weaver Shoal, troughs gained 34,000 m^3 of sand while the crests lost 24,000 m^3, resulting in a net gain within the dredged area of 10,000 m^3. This quantity is similar to that gained for the Crest Polygon "dredging" scenario, but sand deposition associated with the Striped Pattern scenario is spread evenly across the impacted area rather than concentrated at the northeast edge of the "dredged" polygon. Similarly, Isle of Wight Shoal experiences a gain of about 128,500 m^3 of sand accompanied by a loss of 76,000 m^3, resulting in a net gain of 52,500 m^3 of sand within the excavated area. Sand changes associated with Shoal A indicate a gain of about 14,000 m^3 and a loss of 21,000 m^3, resulting in a net loss of 7,000 m^3 of sand. The most likely reason for net loss of sand after "dredging" Shoal A relates to the location of sand excavation on the trailing edge of the shoal. Primary forcing is from the northeast, so a majority of mobilized sand is not supplying sand to the "dredged" area. Most change indicates erosion on the crest and deposition along the leading edge of the shoal to the south. As a result, there is a net loss of sand in the excavated region as sand is transported south to the leading edge of the shoal rather than toward the depressions left by "dredging."

As **Figure 5.35(c)** illustrates, there is very little sediment movement of significance under storm conditions from the east. Morphology change on Isle of Wight Shoal and Shoal A are nearly identical to that identified under previous scenarios. Weaver Shoal shows a minor amount of accretion within troughs at the southwest edge of "dredging."

5.2.6 Discussion

Simulating morphologic changes associated with potential sand mining scenarios on shoals offshore Fenwick Island, Maryland, was accomplished using three interrelated numerical models to develop an understanding of tidal hydrodynamics, wave processes, and sediment transport patterns. More specifically, model coupling was completed to assess the morphologic response of offshore sand shoals to various "dredging" scenarios in support of future beach nourishment requirements.

Tidal hydrodynamics for the continental shelf and nearshore areas offshore the Delmarva Peninsula were modeled using ADCIRC. Model prediction of tidal amplitude and phase offshore Ocean City Inlet was compared with measured data from a NOAA tide gage and found to match well. Average tidal flow velocities observed in the study area are on the order of 0.05 m/s. The direction of flow is observed to be north/northeast on a flooding tide and south/southwest on the ebbing tide. A time series of water surface elevation was taken from these results and used as the hydrodynamic boundary conditions for CMS-M2D modeling.

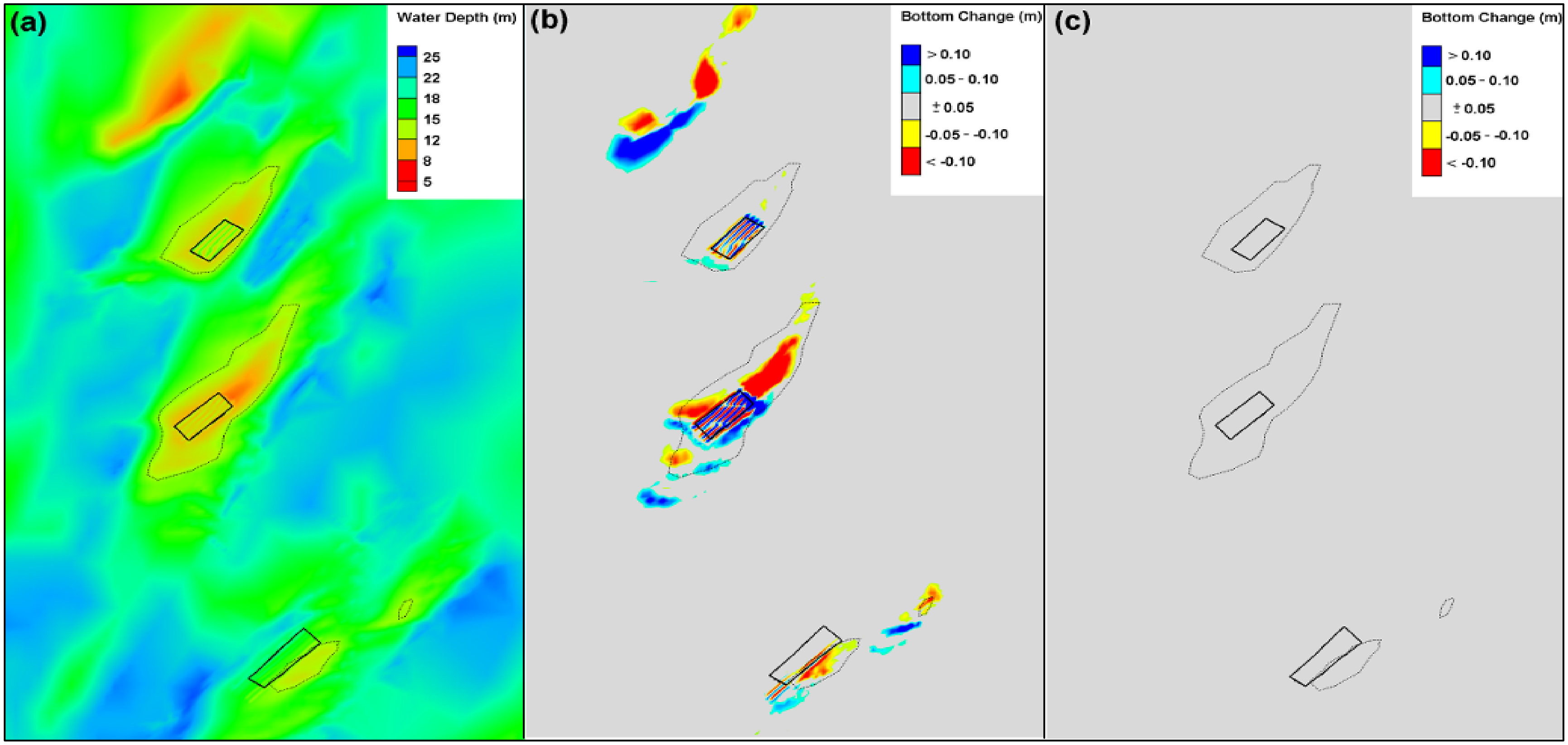


Figure 5.35. CMS-M2D model results for dredging a striped pattern from each shoal showing a) bathymetry at the start of model run, b) the bottom change calculated for the northeast storm condition, and c) bottom change from the easterly storm condition. For reference, all plots show the 12-m depth contour for Weaver, Isle of Wight, and Shoal A. The extents of the dredging areas are also outlined.

With such small tidal velocities so far offshore, incident wave energy played a primary role in sediment movement and morphology change at the offshore shoals. To investigate details of wave transformation throughout the study area, an STWAVE model was developed for the region. Hindcast wave data from WIS Station 161 were used as input to the wave model. A large storm with waves from the northeast (H_{mo} = 6 m) was modeled, along with a storm from the east (H_{mo} = 5 m), to observe differences that incident wave direction has on results. Model results from the northeast storm condition indicate that waves incident from this direction undergo strong wave focusing across the offshore shoals. Wave focusing is primarily the result of waves traveling parallel to bathymetric features, providing ample time for waves to refract as they propagate landward. This phenomenon results in a banded wave energy pattern where there are regions of increased wave height along the shoal crests. Areas of increased wave heights are flanked by regions of decreased wave heights, typically along the southern side of shoal crests and in deeper water lying between shoals. Waves incident from the east propagate perpendicular to shoal orientation, and hence, a more typical wave pattern is observed. There is minor wave focusing and an increase in wave shoaling across the crests of the shoals.

While providing insight into hydrodynamics throughout the study area, the primary purpose for ADCIRC and STWAVE modeling was to provide forcing for the CMS-M2D model so that shoal morphology change could be examined. Bathymetric change at and adjacent to the shoals in response to various “dredging” geometries was of particular interest.

In addition to a Baseline scenario for each of the shoals, three dredging geometries for Weaver and Isle of Wight shoals were simulated, along with two dredging scenarios at Shoal A. Each of these geometries was evaluated under a 3-day storm from the northeast and a 3-day storm from the east **(Table 5.6)**. Results from the Baseline scenario provided insight to the current trends in shoal morphology and migration. Simulations indicate dominant sand transport from northeast to southwest and south, where sand is eroded from shoal crests and deposited on the leading edge of the shoal. This pattern is seen on each of the three shoals in the study area, with Isle of Wight Shoal illustrating greatest change.

Shoal response to imposed dredging scenarios revealed a trend of infilling where “dredging” was performed on areas of the shoal where sediment deposition was indicated under the Baseline scenario. The Crest Polygon scenario examined for Weaver Shoal is a good example, where a simple polygon dredged on the shoal crest did not illustrate much infilling. This result is consistent with sand transport patterns for the Baseline scenario, which showed little deposition on the shoal crest. In contrast, the Baseline scenario showed the leading edge of Weaver Shoal to be a natural depocenter, and when the leading edge of Weaver Shoal was “dredged,” sand was deposited in the excavated area.

Modeling results serve to illustrate that a dredged portion of a shoal will not simply fill because there is a depression present **(Table 5.6)**. If dredging is performed on a portion of a shoal that is not active under baseline conditions, there will be a lack of sand availability to replenish sand removed during borrow site excavation. Imposed storm conditions will not be effective at mobilizing significant amounts of sand in the excavated area, and large-scale shelf processes and major storm events may be the only mechanisms by which “dredged” areas will be filled.

The corollary to this is that material removed from active areas of a shoal will be replenished more quickly by normal wave conditions at the site. Shallow shoal crests, like Isle of Wight Shoal, and the leading edge of all three shoals are noted as the active areas of erosion/deposition. These active transport and deposition areas will recover to original conditions more rapidly than inactive portions of shoals.

Table 5.6. Summary of Numerical Modeling Results.

Dredging Scenario	Storm Condition	**Weaver Shoal** (~9 m deep at shallowest point)	**Isle of Wight Shoal** (~7 m deep at shallowest point)	**Shoal A** (~11 m deep at shallowest point)
Baseline (No Action)	3-day storm from the northeast	Minor deposition on leading margin of the shoal.	Prominent zone of erosion on the north side of the shoal is associated with downdrift deposition along the leading margin of the shoal.	Moderate zone of erosion on the north side of the shoal is associated with downdrift deposition along the leading margin of the shoal.
	3-day storm from the east	No significant seafloor changes.	No significant seafloor changes.	No significant seafloor changes.
Crest Polygon	3-day storm from the northeast	Sand transport from NE to SW, resulting in deposition along the northern polygon boundary. Minor deposition on leading margin of the shoal. Dredged polygon expected to fill from N to S.	Sand transport from NE to SW, resulting in deposition along N and E polygon boundaries. Rapid deposition on leading margin of the shoal. Dredged polygon expected to fill from NE to SW.	Moderate zone of erosion along crest of shoal; deposition along leading edge of the shoal. No observed infilling of the dredged area.
	3-day storm from the east	No significant seafloor changes; long infilling time.	No significant seafloor changes; long infilling time.	No significant seafloor changes; long infilling time.
Leading/Trailing Edge	3-day storm from the northeast	Erosion on the shoal crest enhances deposition in the dredged polygon at the leading edge on shoal migration. Rapid infilling.	Most sand eroded from the shoal crest transported south to the leading edge of the shoal. Minor deposition along the eastern edge of the dredged polygon.	No dredging for this scenario.
	3-day storm from the east	No significant seafloor changes; long infilling time.	No significant seafloor changes; long infilling time.	No dredging for this scenario.
Striped Pattern	3-day storm from the northeast	Sand transport from NE to SW, resulting in deposition along the northern polygon boundary. Minor deposition on leading margin of the shoal. Undisturbed rows in dredged area provide sand for deposition throughout polygon,	Sand transport from NE to SW, resulting in deposition along N and E polygon boundaries. Rapid deposition on leading margin of the shoal. Undisturbed rows in dredged area provide sand for deposition throughout polygon,	Moderate zone of erosion along crest of shoal; deposition along leading edge of the shoal. No observed infilling of the dredged area.
	3-day storm from the east	No significant seafloor changes; long infilling time.	No significant seafloor changes; long infilling time.	No significant seafloor changes; long infilling time.

The Striped Pattern dredging scenario indicated that trenches in excavated areas fill almost uniformly for the length of the “dredged” area. While deposition was greater along the northern edges of excavated trenches, each trough showed deposition for most of its length. Deposition in the center and southern portions of the “dredged” region is a result of sand erosion from undisturbed areas and into adjacent low areas. In terms of timely and uniform recovery of a shoal from borrow site dredging, the striped pattern of sediment removal offers great promise.

6.0 QUESTIONS AND ALTERNATIVES FOR OPTIMIZING PHYSICAL-BIOLOGICAL IMPACTS OF SHOAL DREDGING

(Tim D. Thibaut – Barry A. Vittor & Associates, inc.; Barry A. Vittor – Barry A. Vittor & Associates, Inc.;
David B. Snyder – CSA International, Inc.; and Kenyon C. Lindeman – Florida Institute of Technology)

While formulating monitoring protocols for dredging projects targeting sand shoals, Research Planning, Inc. et al. (2001) identified several information gaps concerning physical and biological effects. Several questions derived from these information gaps are addressed in this section using literature reviews and, where applicable, modeling results. The management goal is to efficiently mine or dredge sand from shoals in a way that will lessen the severity and duration of biological impacts and be conducive to timely and realistic biological recovery. Physical impacts caused by dredging sand shoals on the continental shelf broadly include changes in hydrodynamics, grain size composition, and seafloor topography. All of these physical alterations affect biotic assemblages at a variety of spatial scales within and among shoal features.

6.1 IS THERE A PREFERRED MANNER TO REMOVE SAND FROM A SHOAL/RIDGE FEATURE TO MAXIMIZE THEIR USE AND MAINTAIN THE INTEGRITY OF THE FEATURE?

The analysis of dredging scenarios presented in **Section 6.3** indicates that removing sand from the leading edge or crest of a shoal is the preferred extraction scenario. However, all proposed dredging approaches ensure that a topographic irregularity is maintained to promote long-term shoal development. Hayes and Nairn (2004) and Research Planning, Inc. et al. (2001) identified a potential concern regarding the degree of offshore sand mining on ridges and maintenance of ridge morphology. They suggested that there may be a limit beyond which removal of significant quantities of sand from ridges may lead to “deflation” or eventual disappearance of the ridge. Because all published literature on shelf sand ridges emphasize modern depositional processes when describing formation and maintenance of these features (based on coring and seismic data), the mechanism by which shoal “deflation” would occur is unknown, unless the entire shoal was physically removed. As long as a seafloor irregularity remains upon which to reform the ridge, dominant shelf processes will construct these features as described by all shelf ridge process models (see **Section 1.1**). Therefore, losing the original structure of a dredged sand shoal should not be a concern for managers unless the entire feature is removed.

6.2 ARE THERE BENTHIC BIOLOGICAL DIFFERENCES THAT RUN LONGITUDINALLY ALONG THE RIDGE AND SHOAL FEATURES SUCH THAT DREDGING OPERATIONS SHOULD BE TAILORED TO AVOID CERTAIN AREAS?

Benthic stations in the study area show some consistency in community composition along the longitudinal axes of shoals, but there are differences in community patterns comparing the current-facing and lee sides of shoals. The leading edges of Weaver and Isle of Wight Shoals in particular have steep slopes, with coincident changes in resident macrobenthos to the south of the shoals. On the lee side of Weaver Shoal there are aggregations of tube-building polychaetes, areas of shelly sediments, and sand ripples that provide refuge for motile assemblages of epifauna (Diaz et al., 2003). Mining sites that have structural complexity may be less favorable in ecological terms than targeting other subareas of a shoal with homogenous coarse sand habitat. Removal of habitat structure in relatively heterogeneous soft-sediment systems may potentially decrease local biodiversity (Thrush et al., 2001). In addition, the lee sides of area shoals are relatively sheltered from the prevailing hydrographic regime. Mining in these areas may result in dredging sites that are depositional due to hydrodynamic flow deceleration that occurs on the lee side of elevated bedforms (Abelson and Denny, 1997). Such sediment deposition could potentially result in burial of benthic organisms.

The presence of shoals affects patterns of distribution of benthic fauna. Similar to the study area, subtidal systems in other locations have lower faunal abundance and diversity on shoals compared to the surrounding seafloor (Boesch, 1979; Viscido et al., 1997; Kaiser et al., 2004). Community structure of subtidal sediments is controlled primarily by benthic disturbances and physical stresses (Whitlatch, 1977; Probert, 1984; Thrush et al., 1996), and habitats affected by harsh physical forces may exhibit less diversity than more stable environments (Sanders, 1968). Cross-shelf changes in benthic community patterns are well documented (Day et al., 1971; Flint and Holland, 1980; Wigley and Theroux, 1981; Tenore, 1985), including increases in diversity with greater depth. The occurrence of more diverse benthic communities in deeper water is presumably due to more stable hydrographic conditions compared to shallow turbulent zones (Day et al., 1971; Flint and Holland, 1980). A high-disturbance with dynamic low diversity may also occur within areas of relatively minor change in absolute depth, due to local bathymetry. Since shoals are higher than the adjacent seabed, they are exposed to more turbulence from storm-generated waves and currents. Benthic shear flow and its related physical parameters (sediment regime, sediment stability, pore water oxygenation) have strong controlling effects on the composition of benthic invertebrate assemblages (Hall, 1994; Snelgrove and Butman, 1994). The ecologies of shoal fauna may reflect the energetic hydrodynamics of these locations. Shoal crest constituents include suspension-feeding fauna such as tunicates, surf clams, and sand dollars, as well as agile burrowing amphipods and lady crabs.

Because of greater exposure to wave-generated turbulence, the benthic community may generally recover more rapidly in mined sites on shoal crests, compared to lower areas of the shoals. In coarse sediment habitats with strong currents, subsurface hydrology provides deeper oxygenation and more rapid flushing of interstitial water. Higher locations on shoals may therefore have more rapid amelioration of degraded surface and pore-water hydrology that often results from dredging. Higher portions of the shoals also experience greater sediment mobility, potentially resulting in more rapid sediment reworking and infilling of dredged sites. Moreover, episodic accumulations of organic material, which may increase biological oxygen demand and result in hypoxia or anoxia, may be less likely to persist in a site that is exposed to greater turbulence. Collie et al. (2000) reviewed numerous published studies investigating fishing gear effects on benthic habitats and found that faunal recovery appears most rapid in less physically stable environments. Absent of any management concerns of mining sediments from shoal crests, it may be most advantageous to select those dynamic sites with potential for more rapid post-dredging recovery.

6.3 ARE THERE PROCEDURES TO DREDGE SHOAL AND RIDGE FEATURES THAT WILL MINIMIZE ECOLOGICAL IMPACTS AND/OR SPEED RECOVERY?

To address this question, results of dredging scenarios described in **Section 5.0** for infilling amounts and rates were examined. The four scenarios were as follows

- Dredging a hole over a restricted area on the crest of a shoal, equivalent to standard approaches to dredging a shoal;
- Dredging the leading edge of a shoal;
- Dredging the trailing edge of a shoal; and

- Dredging in a striped pattern to facilitate recruitment of benthic invertebrates into dredged areas.

In summary, the most desirable location or subarea (crest, leading edge, or trailing edge) of a shoal for dredging is the leading edge. This is due primarily to net long-term deposition and faster infilling rates of dredged areas. The crest would be a second choice followed by the trailing edge. In terms of the dredging removal method, the striped pattern showed the most promise with respect to infilling rate. Shallow striped areas in the modeling scenarios rapidly recovered to pre-dredging levels. There are other system drivers that may influence differing measures of biological recovery including variability in supply, transport, and settlement of larvae for some species on a spatial scale that greatly exceeds the shoal area itself.

Physical results of each modeling scenario are described in the following subsections along with a discussion relating potential biological response to those results. A primary emphasis in analyzing biological response was potential for recovery to pre-dredging conditions. A brief discussion of direct and indirect recovery and the nature of recovery of dredge-related impacts is provided herein.

Dredging shoal areas directly affects existing infauna, epifauna, and fish assemblages. For example, entire infaunal assemblages are directly removed with the mined sand during dredging. Epifauna including crabs, shrimps, and some demersal fishes may also be removed from dredged areas through entrainment. Loss of invertebrates and fishes translate into decreased prey items for larger fishes and would be considered an indirect effect. Many of the federally managed species discussed in **Sections 4.2** and **4.3** are demersal feeders and will be indirectly affected.

In addition to direct loss of organisms and indirect effects through dredging are changes in shoal topography and circulation patterns that would impact fishes and invertebrates that utilize shoals in different ways. Changes to the topography of a shoal may result in redistribution of invertebrates and fishes that oriented to current patterns created by individual shoal features. It is likely that some fishes use shoals as guideposts or orientation points during spawning or cross-shelf migrations.

An important characteristic of marine communities is their resilience, or the capability of returning to an initial state following a disturbance. Although the recovered states will vary in terms of species composition and possibly trophic function, differences reflect variability inherent in the assembly of all natural communities. Marine organisms will successfully recolonize unoccupied space if that space provides necessary ecological requirements for individual species. Because most species possess a two-phase life cycle consisting of a sedentary benthic phase and a dispersive planktonic phase capable of moving great distances from the natal area, there are potential colonists always available in the local and regional species pool. Nonplanktonic immigrants (motile invertebrates, adult, and juvenile fishes) from nearby habitats may also recolonize disturbed areas.

Recovery includes reassembly by various species leading to reestablishment of infaunal, epifaunal, and fish assemblages. A major premise of the recovery process is that if the physical habitat structure is restored to a facsimile of the pre-dredging condition, biota will follow suit. Due to natural variability, this may be only partially true and some areas may be more productive than other structurally similar areas (Stoner, 2003). Nevertheless, for this study it was assumed that restoring physical conditions would lead to an acceptable ecological recovery and that infilling of dredge areas was a key factor contributing to that process.

Dredging removes sediments and benthic invertebrates, and there must be some degree of physical recovery before benthic recolonization occurs (Newell et al., 1998). The nature of biological recovery after dredging, will depend in part on site topography and its orientation to the prevailing hydrographic regime. Bottom shear generally slows hydrodynamic flow as currents move across seafloor depressions (Nowell and Jumars, 1984; Grove et al., 1991; Abelson and Denny, 1997), such as those created by dredging. Flow regime in the benthic boundary layer is an important factor regulating the composition of soft sediment benthic assemblages (Nowell and Jumars, 1984; Hall, 1994; Snelgrove and Butman, 1994; Newell et al., 1998; Crimaldi et al., 2002; Hentschel and Herrick, 2005). Bathymetric depressions formed by dredging may create a potentially depositional habitat with relatively limited sediment mobility. Depressions often support faunal assemblages that differ from nearby areas without depressions (Boesch, 1972; Camp et al., 1977; Wigley and Theroux, 1981; Auster, 1987; Lyons, 1989; Auster et al., 1991; Able and Kaiser, 1994; Byrnes et al., 2000; Diaz et al., 2003).

Benthic community patterns vary with location on and near the shoals, in part due to variable exposure to the prevailing hydrodynamic regime. Since the target sites vary in shoal location and pattern of excavation, there are potential implications for the ecological consequences of dredging among the alternative mining scenarios. The nature of biological recovery, including the speed of colonization and the composition of the recovered community, will depend in large measure on physical characteristics of a site after dredging. Biological recovery can be inferred from physical measurements such as post-dredging bathymetry, near-bottom microcirculation, and the rate and nature of infilling of excavated sites, as well as an array of biological measures that interface with these physical processes including larval recruitment, compositional similarity, and trophic interactions.

Although much attention has been given to turbidity effects from dredging, most discussions have focused on estuaries, embayments, and enclosed waters (e.g., Sherk and Cronin, 1970; Sherk, 1971; Sherk et al., 1975; Moore, 1977; Peddicord and McFarland, 1978; Stern and Stickle, 1978; Herbich and Brahme, 1991; LaSalle et al., 1991; Kerr, 1995; Newcombe and Jensen, 1996; Wilber and Clarke, 2001). Turbidity effects appear less important in unprotected offshore areas for several reasons. Offshore sands tend to be coarser, with less clay and silt than inshore areas. The open ocean environment also provides more dynamic physical oceanographic conditions, which minimize settling effects. In addition, offshore organisms are adapted to sediment transport processes, which create scouring, natural turbidity, and sedimentation under storm and normal conditions. As such, impacts should be evaluated in light of natural variability as well as high-level disturbances associated with such events as storms, trawling, and floods (Sosnowski, 1984; Herbich, 1992).

6.3.1 Dredging a Hole Over a Restricted Area on the Crest of a Shoal, Equivalent to Standard Approaches to Dredging a Shoal

To model the potential for benthic habitat recovery, the crest of Weaver Shoal had a simulated excavation depth of 3 m below ambient grade, whereas a larger area of the crest on Isle of Wight Shoal was excavated to a depth of only 2 m. Despite a deeper excavation, simulated infilling during a major storm event was substantially greater at Isle of Wight Shoal (40,000 m^3) compared to Weaver Shoal (8,000 m^3). Under the modeled scenarios, physical and thus benthic recovery may occur more rapidly with a crest excavation on Isle of Wight Shoal compared to Weaver Shoal. Shoal A shows little change in morphology due to a major storm compared with the Baseline scenario. Compared to Weaver Shoal and Isle of Wight Shoal, the benthic community in an excavated site on the crest of Shoal A may take longer after dredging to attain similarity with adjacent nondredged areas due to potential for slower infilling.

Until some degree of infilling and new recruitment events occur, excavated sites will undergo substantial short-term declines in abundances of those species partially removed by the dredging. During these recovery periods, the excavation site may support benthic assemblages that differ from adjacent nondredged areas of the shoals. The time required to attain a condition that is similar to adjacent nondredged areas of the shoals may depend particularly on episodic turbulence due to storm-generated wave action.

Modeling in the present study indicates that during a major storm from the northeast, both Weaver Shoal and Isle of Wight Shoal will experience sand transport southward into their respective dredged sites on the crest. There is greater infilling at the northeast extent of the dredged sites, and little deposition in the central portions of the excavated areas. It is expected that as the dredged areas continue to fill during successive storms, the southern extent of the dredged areas of Weaver and Isle of Wight Shoals would be the last regions to fill.

Infilling of disturbed sites may be a significant component for attaining a biological condition similar to adjacent nondisturbed areas (Veer et al., 1985; Newell et al., 1998; Dernie et al., 2003; Boyd et al., 2005), provided that the imported sediments are similar to the sediments of the surrounding area (Veer et al., 1985; Hall, 1994; Van Dalfsen et al., 2000; Boyd et al., 2005). Sedimentary habitat (particle size, degree of sorting, organic content) often has a strong correlation with benthic assemblage composition. If the sedimentary habitat of the infilled site differs from the pre-dredging condition and that of the surrounding area, the reestablished community in a dredged site may differ from adjacent nondredged areas. The sediment source for infilling dredged sites of the study area is shoal material. Because the sediment regime of the recovered dredged sites would be similar to that of the unaffected portions of the shoal, long-term (i.e., years) community composition effects due to sedimentary habitat differences with nondredged areas of the shoals are unlikely. For fishes, the creation of substantial vertical relief may be utilized by various species to take advantage of feeding or shelter opportunities at small fronts created by angular relief or other indirect habitat features.

A persistent state of altered benthic community composition in mined sites would most likely be due to effects of local microcirculation changes caused by slowed hydrodynamic flow across the excavated areas, coupled with biological processes. Though the study area has limited amounts of very fine sediments, there is potential for fine materials to accumulate in dredged sites and degrade habitat quality (Veer et al., 1985; Barry A. Vittor & Associates, Inc., 1999).

Reduced flow velocity across the dredged site may affect larval invertebrate behavior and settlement (Butman, 1987; Abelson and Denny, 1997) as well as fishes that undergo early larval settlement (Lindeman et al., 2001; Kingsford et al., 2002); and attract other motile macrofauna (Camp et al., 1977; Lyons, 1989; Diaz et al., 2003). Potential ecological benefits of swales and depressions include better individual control of motility in less turbulent locations (Auster, 1987; Weston, 1988; Auster et al., 2003), increased foraging efficiency due to more efficient chemosensory processes (Moore et al., 1994; Weissburg et al., 2002; Hazlett et al., 2006), and greater refuge value due to increased spatial complexity (Jacobi and Langevin, 1996). Regardless of the actual species composition of the recovered benthic community, the assemblage composition of dredged sites would change through time, as occurs naturally in sedimentary habitats of the open shelf. Demersal fishes would be expected to forage in recovering areas opportunistically in relation to species-specific characteristics of body size and diet. These changes would reflect reassembly of invertebrate communities and alterations of food web architecture over time.

The relationship between abundance of fishes and invertebrates on crests in comparison to flanks is complicated by an absence of direct information and the dynamics of the physics and biological responses of these areas. The important structure-building worm, *Diopatra*, does not appear to show high concentrations on crests (VIMS, 2000). The tube-dwelling polychaete *Asabellides* commonly forms mats in the intershoal trough areas but does not occur on high areas of shoals. Some motile burrowers, such as lady crabs and certain amphipods, may have higher concentrations on crests (Viscido et al., 1997; VIMS, 2000). Developing more information on the comparative roles of flank and crest habitats and their difference on leading edge versus trailing edge slopes should be a priority in assessing environmental impacts on differing shoal habitats.

6.3.2 Dredging the Leading Edge of a Shoal

Under a significant storm from the northeast, the greatest deposition on the leading edge of Weaver Shoal was observed along the southwest face of the shoal, with a thin band of accretion also appearing along the southeast margin of the "dredged" area. This pattern is similar to that observed in other excavation scenarios, with the exception being that most deposition occurs closer to the crest of the shoal as a result of the dredged region extending toward the crest.

The leading edge of Weaver Shoal transitions to a steep slope, leading to a deep area on the southeast side of the shoal. There is an abrupt change in benthic community composition across a relatively short horizontal distance from the shoal crest to the backside slope and swale area, presumably due to changes in depth and microcirculation patterns. Bathymetric features as small as sand ripples affect near-bottom circulation due to wave-induced shear stress (Pana et al., 2007), and local microcirculation changes may affect the composition of benthic assemblages in sedimentary habitats (Nowell and Jumars, 1984; Barros et al., 2004). The presence of an elevated bedform such as Weaver Shoal causes flow to accelerate as water moves toward its widest cross-section (Abelson and Denny, 1997). But on the downstream (lee) side, flow decelerates creating a current shadow (Grove et al., 1991).

Comparing the two scenarios for Weaver Shoal, simulated infilling was greater for an excavation of the leading edge (26,000 m^3) compared to the shoal crest (8,000 m^3). Mining the leading edge of Weaver Shoal may involve trade-offs between more rapid infilling and increased potential for prolonged community alteration, due to being relatively sheltered from strong northeastern currents.

Current shadows occur when high current velocities dissipate shed eddies, leaving an area of low current velocities on the lee side of a bedform. Because of its more sheltered location on the southeast side of Weaver Shoal, mining the shoal's leading edge has greater potential over time to accumulate particulate organic material or very fine (mud and silt) sediments, compared to excavation on shoal crests or lower areas on the current-facing side of the shoals. An increase in the silt, mud, or organic content of surface sediments would likely prevent community recovery to a state that is similar to the adjacent nondredged substrata (Veer et al., 1985; Barry A. Vittor & Associates, Inc., 1999). Even without infilling of very fine material, composition of the recovering assemblage in a leading edge dredge site may differ from the adjacent area due to changes in hydrodynamic flow characteristics (Snelgrove and Butman, 1994).

Community composition in deeper areas on the lee side of the shoal can reflect diminished bottom shear flow. Swales in the study area have relatively high organic content and higher proportions of sediment fines, and support greater individual abundance, numbers of taxa, and biomass compared to shoal crests (VIMS, 2000). Aggregations of tube-builders inhabit deeper areas on the lee side of Weaver Shoal. Given sufficient time, reduced hydrodynamic flow and possibly organic enrichment in a leading edge excavation may facilitate colonization by deposit-feeding benthos characteristic of swales, including tube-dwelling amphipods (*Ampelisca* spp. and *Unciola* spp.) and the polychaete *Asabellides oculata*. It is assumed that if such an assemblage became established it would eventually be buried by infilling of the dredged site, yet this may vary among shoals and time periods. These patches of tube dwelling organisms provide structural habitat for small fishes and other organisms (e.g., Diaz et al., 2003).

Fishes that normally occur in the water column such as striped bass, bay anchovy, Atlantic menhaden, Atlantic mackerel, Spanish mackerel, or spiny dogfish may utilize the current shadow as refuge from high velocity waves and currents. Excavation of the leading edge could lead to basic changes in the nature of the current refuge or even elevated, albeit short term, turbidity that would degrade the habitat value. The relative usage patterns of flanks and crests by fishes that use current shadows in the water column currently is poorly known, though flanks of lee sides would seem to have value for species trying to physically remain within a current shadow.

6.3.3 Dredging the Trailing Edge of a Shoal

The trailing edges of study area shoals are largely erosional under natural conditions, supplying sand to the shoal crests and leading edges. Sediments therefore may not be as readily replaced at dredge sites on the trailing edge compared to locations on the crest or leading edge of a shoal. Prolonged bathymetric alteration after excavating a seafloor site may result in persistent changes in benthic community composition (Veer et al., 1985; Barry A. Vittor & Associates, Inc., 1999; Dernie et al., 2003). Mining on the trailing edge of Weaver Shoal, or generally in sites that are naturally erosional, may result in longer periods of benthic community alteration after cessation of dredging, due to slow infilling.

For a trailing edge excavation on Isle of Wight Shoal there are small areas of accretion along the periphery of the dredged area closest to the crest. Most of the sediment moved from the crest is deposited along the southeast face of the shoal. There is little forcing during this event to move suspended sediment over the crest to the north and into the “dredged” area. Compared to crest and striped pattern excavation scenarios, dredging the trailing edge at Isle of Wight Shoal may prolong the time required for infilling the excavated site. Compared to other scenarios, therefore, dredging the trailing edge may prolong the duration of benthic assemblage alteration due to dredging.

6.3.4 Dredging in a Striped Pattern to Facilitate Recruitment of Benthic Invertebrates into Dredged Areas

A series of long parallel cuts made in a striped pattern would create a greater amount of microhabitat in terms of surface area than other dredging methods. However, near-term physical disturbances could substantially reduce the seeming microhabitat surface area. Species-specific invertebrate and fish microhabitat use of these different types of edges requires further investigation. For the striped pattern model runs, excavated troughs began to fill while the undisturbed regions between the troughs were eroding. Sand deposition associated with the Striped Pattern scenario is spread evenly across the impacted areas rather than concentrated at the northeast edge of the “dredged” polygon, as in other scenarios. Deposition in the center and southern portions of the excavated areas results from redistribution of sand from undisturbed areas between the troughs into adjacent low areas.

Leaving relatively undisturbed areas interspersed throughout a dredged site should provide some pools of potential colonists within the boundary of the overall dredge area. The rate of benthic recolonization largely depends on the sizes of the pools of available colonists and temporal variability in spawning and recruitment, and the importance of different recruitment processes varies across spatial scales (Smith and Brumsickle, 1989; Günther, 1992; Whitlatch et al., 1998; Zajac et al., 1998; Palma et al., 1999; Norkko et al., 2006). Larval recruitment increases in importance with increasing size of a disturbed area (Smith and Brumsickle, 1989; Günther, 1992), whereas post-larval, juvenile, and adult migration across the seabed is more limited across large spatial scales (Smith and Brumsickle, 1989; Günther, 1992; Whitlatch et al., 1998). It is thus assumed that differences in the relative dispersal ability of different life stages should vary with the spatial scale of physical disturbance (Whitchlach et al., 1998; Norkko et al., 2006). Such scale-dependent variability has potentially significant implications for biological recovery of disturbed areas (Levin, 1984; Smith and Brumsickle, 1989; Günther, 1992; Hall et al., 1994; Thrush et al., 1996; Pranovi et al., 1998; Whitlatch et al., 1998; Zajac et al., 1998; Dernie et al., 2003; Norkko et al., 2006). This scenario maintains a patch structure that would be attractive to, and likely promote the survival of fishes emigrating into and settling on the recovering areas. As discussed above for invertebrates, variation in larval supply that is related to adult spawning in distant and nearby waters will significantly determine how the recovering borrow areas are ultimately colonized (Steves et al., 1999).

Survivorship of post-settlement juveniles and adults in some cases plays a large if not determinant role in regulating patterns of benthic community composition (Ólafsson et al., 1994), and survival of post-larval migrants is potentially important in the benthic recovery process (Van Dolah et al., 1984; Cummings et al., 1995; Whitlatch et al., 1998; Jutte et al., 2002; Stocks, 2002). A large number and variety of soft-bottom macrofauna undergo post-settlement dispersal, including species such as surf clam (Snelgrove et al., 1999). Even characteristically nonopportunistic species can assume opportunistic behavior during the initial phase of the recolonization processes of disturbed areas (Wu and Shin, 1997; Pranovi et al., 1998; Beukema et al., 1999). Decapods and other motile epifauna would recruit into mined sites as physical conditions recover sufficiently to provide suitable habitat. Decapods in particular are highly dispersive beginning during juvenile stages, actively seeking and using complex habitats after settlement (Hedvall et al., 1989; Palma et al., 1999; Heck et al., 2001; Pardo et al., 2007). Minimizing the seabed distance across which crawling or burrowing fauna must migrate into dredged sites in general should promote more rapid benthic community recovery after dredging.

In summary, based on geological models of shoal formation there does not appear to be a mechanism supporting the idea that the structural integrity of a feature will “deflate” or “unravel” when subject to repeated dredging. Benthic biological differences are expected to occur along the longitudinal axis of a shoal reflecting the differences that occur across the feature. For example, the leading edge, crest, and trailing edge would likely support distinctive assemblages and, although variable, these assemblages would be expected to persist longitudinally. This suggests that depending on the spatial nature of the individual dredging project, additional stratification should be considered when designing monitoring programs.

In summary, the most desirable location or subarea (crest, leading edge, or trailing edge) of a shoal for dredging is the leading edge. This is due primarily to net long-term deposition and faster infilling rates of dredged areas. The crest would be a second choice followed by the trailing edge. In terms of the dredging removal method, the striped pattern showed the most promise with respect to infilling rate. Shallow striped areas in the modeling scenarios rapidly recovered to pre-dredging levels. There are other system drivers that may influence differing measures of biological recovery including variability in supply, transport, and settlement of larvae for some species on a spatial scale that greatly exceeds the shoal area itself.

7.0 RECOMMENDATIONS FOR ENGINEERING OPTIONS AND MITIGATION MEASURES

(Mark R. Byrnes – Applied Coastal Research and Engineering, Inc.; Tim D. Thibaut – Barry A. Vittor & Associates, Inc.; Barry A. Vittor – Barry A. Vittor & Associates, Inc.; and Kenyon C. Lindeman – Florida Institute of Technology)

Numerical modeling and field data may be used to suggest engineering options and mitigation measures to avoid deleterious impacts of offshore dredging within the ridge and shoal features on the Federal OCS (MMS, 2003). Bathymetry data may provide information on natural sediment transport patterns and site-specific aspects of shoal and ridge migration characteristics. Physical modeling can provide information to assess potential infilling rates of dredged sites, an important component of ecological recovery (Byrnes et al., 2004). Biological surveys provide benthic and water-column assemblage composition data and consideration of various life history features may be used to formulate reasonable assessments of potential recovery dynamics (Diaz et al., 2004).

Mitigation measures designed to minimize or avoid adverse consequences to natural physical processes and benthic biological resources may include targeting shoal and ridge locations that may be less susceptible to prolonged physical alteration, compared to the natural condition. The nature of biological recovery, including the speed of colonization and benthic assemblage composition, particularly for invertebrates and demersal fishes, will depend in large measure on the physical characteristics of a site after dredging. The level of coupling between bottom-associated assemblages and those of the mid- and upper-water column (e.g., pelagic fishes and squid) is not well known on trophic and larval scales and can vary in complicated manners (Witman et al., 2004). Focusing on minimizing physical impacts and their duration as a way to minimize biological consequences recognizes the potential role of understudied, biophysically coupled events that may occur undescribed or unmonitored on the shoals. Many prominent fish species are relatively opportunistic in space use (Able, 2005; Able et al., 2006) and, in addition, are making massive long distance migrations across a wide shelf every 6 months. With minimization of physical alterations through the use of engineering options and mitigation strategies, persistent changes in community patterns and ecological impairment may be avoided during and after sediment mining.

Targeting shoal and ridge locations that may be less susceptible to prolonged physical alteration to presumably speed biological recovery is a valid approach to evaluate dredging consequences. There are other system drivers including variability in larval recruitment (larval supply, transport, and delivery) that for some species, occur on a spatial scale that exceeds the recovery drivers in a particular shoal area. The definitions and measures of recovery will be important to any future mining of these shoals. Metrics of recovery should be selected to reflect community-wide as well as individual species response to environmental changes caused by mining and subsequent recovery. Because of lack of replication and issues with finding appropriate reference areas, study designs should consider before-after-control-impact (Osenberg et al., 2006) to measure recovery.

7.1 SPATIAL SCOPE OF POTENTIAL CONSEQUENCES

The primary environmental consequences of dredging shoals and ridges appear to be predominantly limited to the immediate area of mined sites. Large-scale impacts of sand mining in OCS waters have not been documented to date. Studies evaluating changes in wave and current processes relative to sand mining on offshore shoals have found no significant changes in regional sand transport patterns (Hayes and Nairn, 2004; Kelly et al., 2004).

In some circumstances, suspended solids introduced into the water column by dredging may be transported to adjacent areas by water currents. The probability of significant adverse consequences of turbidity will vary with regional differences in the proportion of fine sediments and organic material at target sites, and local currents and wave climate. Shoals in the study area tend to have coarse sediments with low amounts of clay, silt, and organic material, and dredging-induced turbidity is expected to be negligible in the open oceanic waters offshore Maryland and Delaware (VIMS, 2000).

In areas with greater amounts of fine sediments, alternative dredging equipment and methods may be used to limit transport and redeposition of suspended solids. In general, cutterhead suction dredges produce less turbidity than hopper dredges though they excavate deeper. Well designed and properly operated cutterhead dredges can limit sediment suspension to the lower portion of the water column. Slow dredging methods also may be used to minimize spillage that can increase turbidity near the dredge (**Section 2**).

Where far-field sedimentation is minimized, the biological consequences of sand mining are likely to be limited to the immediate area of dredged sites (Newell et al., 1998). Mined sites will undergo substantial short-term declines in abundances of the benthic populations partially removed by the dredging. Long-term effects have not been frequently measured. Biological impacts are largely limited to a dredged site in offshore shoal areas of the shelf because the dredge removes only a portion of the resident inner shelf populations, primarily infaunal invertebrates and potentially some sand-dwelling fishes. The mid-water and bottom dynamics of organics within any plumes and the fill path itself are essentially unmeasured. Pathways of energy flow among invertebrate and fish components of the food web, for which there is some information from the region (Link, 2002), are interrupted for unmeasured periods of time in mined sites due to removal of benthic invertebrates and dredging-interrupted prey predator relationships among invertebrates and fishes.

7.2 IMPACTS AT INDIVIDUAL RIDGES AND SHOALS

There are limits to the amount of sand available from any single ridge or shoal if the feature is to be maintained. As long as a seafloor irregularity remains upon which to reform the ridge, dominant shelf processes will construct these features as described by shelf ridge process models. For a given dredging and beach nourishment interval, it therefore is advisable to remove only a portion of a particular ridge or shoal (**Sections 3** and **5**).

For a given ridge or shoal, project elements such as target site location, dredging depth, and excavation patterns may be designed to avoid persistent physical alteration after cessation of dredging. Recommendations for selection of target sites and dredging methods to avoid or minimize adverse physical consequences may include:

- Extract sand from a depocenter, or leading or downdrift margin of a shoal, to avoid interrupting natural shoal migration and potentially reduce the time required for site refilling;
- Avoid dredging in erosional areas that source downdrift depocenters, which also may be slow to refill after dredging;
- Shallow dredging over large areas rather than excavating small but deep pits; and
- Dredge in a striped pattern to leave sediment sources adjacent to and interspersed throughout target areas, leading to a more uniformly distributed infilling process.

Borrow site geometry should be considered when assessing physical impact producing factors for a particular shoal or ridge. While a relatively shallow excavation over a wider area results in more surface area disturbance and greater short-term biological impacts, sediment reworking and site infilling in general may proceed more rapidly than would occur with deeper, more spatially restricted dredging (Byrnes et al., 1999). In particular, dredging a bathymetrically abrupt pit can greatly extend the duration of physical modification and community alteration (Barry A. Vittor & Associates, Inc., 1999). Considering shallower excavation options across wider areas, infilling rate may be dependent on site-specific factors. In the current study, simulated infilling at Isle of Wight Shoal was substantially greater than was modeled for Weaver Shoal, and therefore even with a deeper excavation at Isle of Wight Shoal, complete infilling may occur more rapidly than in a shallower excavation at Weaver Shoal. Depending on shoal or ridge morphology, regional hydrodynamic processes, and biological community composition and temporal dynamics for a given target area, it may be necessary to evaluate how to balance short- and long-term physical and biological impacts related to depth of excavation (Michel et al., 2007).

Infilling of mined sites reestablishes natural near-bottom hydrodynamic shear flow, and is an important process for potentially attaining a biological condition similar to adjacent nondisturbed areas. When designing sand mining projects on ridges and shoals of the OCS, information on geomorphology and hydrodynamic processes is needed regarding the stability of the feature.

With bathymetry data that are sufficient to assess natural sediment transport patterns, depocenters may be targeted and erosional areas avoided on shoals and ridges. Extracting sand from a depocenter implies that recovery or infilling processes would proceed in a way consistent with natural long-term depositional processes for a borrow site location. In the current study area, bathymetry data indicate that the leading edge of Weaver Shoal has an extensive depositional area along its southern margin. Such sites may be ideal locations for sand mining because dredging would occur in an area of active natural deposition, which would promote infilling after cessation of dredging.

Bathymetric change data analyzed for the Weaver Shoal study area suggest that the eroding portion of a shoal’s trailing edge may be an area to avoid, because dredging in these areas may have a direct impact on natural erosion processes that source downdrift depocenters. Dredging trailing or otherwise naturally eroding locations may therefore disrupt natural shoal evolution, and dredging a trailing edge may prolong the duration of benthic community alteration due to relatively slow infilling, compared to leading edge or crest excavations.

Currently, however, there is no information about biological recovery responses in erosional trailing edge and accretional leading edge shoal areas. Therefore, it is unknown whether there are substantive differences in critical biological processes such as recruitment success and post-settlement mortality in leading and trailing edge habitats. For example, are there skewed differences in recruitment success and variability for primary invertebrates and fishes between leading and trailing edge areas? These could be fruitful questions for future modeling and field investigations.

Borrow site orientation to the prevailing hydrodynamic regime may be considered when assessing physical impact producing factors, and thus potential biological consequences, for a particular shoal or ridge. In the Weaver shoal study area, the leading edges of the shoals are steep, leading to intershoal troughs to the southeast. At these relatively sheltered locations on the lee side of the shoal, current flow slows. Because of a current shadow in these areas, mining a leading edge has greater potential over time to accumulate particulate organic material or very fine sediments in a borrow site, compared to excavation on shoal crests or lower areas on the current-facing side of the shoals. Mining a leading edge may involve trade-offs between more rapid infilling and increased potential for prolonged community alteration.

The usefulness of dredging in a striped pattern to speed physical and biological recovery is largely untested. However, modeling indicates that, compared to a continuous excavation pattern, dredging in a striped pattern may promote transport and redistribution of sediment after dredging. A striped pattern excavation may lead to a uniformly distributed and more rapid infilling process compared to continuous excavation. More rapid reestablishment of ambient topography and benthic shear flow would facilitate recruitment of fauna characteristic of nearby nondredged areas. Much evidence indicates that there is strong local control of recruitment, particularly for post-larval life stages that are believed to be important colonizers of disturbed areas. Minimizing the seabed distance across which crawling or burrowing fauna must migrate into dredged sites in general should promote more rapid benthic community recovery after dredging. Compared to a continuous excavation, a striped pattern may also increase the surface area of sedimentary habitats and microhabitats used by a wide array of invertebrates and fishes during early and adult life stages.

Further consideration of striped dredging profile is recommended. Determining details of flank and crest coverage in terms of surface area and pattern will require future site-specific physical and biological analyses.

Because of greater exposure to wave-generated turbulence, the benthic community may recover more rapidly in mined sites on shoal crests compared to lower areas of the shoals. Higher locations on shoals and ridges experience greater sediment mobility, potentially resulting in more rapid sediment reworking and site infilling. Shoal and ridge crests in the Weaver Shoal study area also tend to support less diverse and presumably more resilient invertebrate assemblages than those found in surrounding areas of the shoals.

7.3 RECOMMENDATIONS FOR IMPROVING EFH MANAGEMENT

Shoals and ridges serve as a benthic nursery area, refuge, and feeding sites for a variety of ecologically important and commercially and recreationally harvested fish and invertebrate resources (Diaz et al., 2004; Able et al., 2006). Issues requiring consideration in the development of EFH Assessments prepared for excavation on OCS shoals should, at a minimum, include analysis of those EFH species and life history stages already identified for shoal and ridge features. Several management agencies have identified sandy shoals as EFH for migratory benthic fishes, including flounder and sharks (**Section 4.5**). To the south of the study area, the South Atlantic Fishery Management Council has also identified shoals as EFH for migratory pelagic fishes, including king mackerel and Spanish mackerel.

For most managed species relatively little is known regarding the use of shoals and ridges as EFH. However, substantial information is available and impact assessments can be developed. The recommended minimum content for an EFH Assessment should include the affected habitat and species (by life history stage); an analysis of direct, indirect, and cumulative effects; a literature review including relevant population impact processes; and an analysis of alternatives to the proposed action.

In assessing the consequences of sand mining on EFH of shoal and ridge systems of the Federal OCS, thorough analysis requires more than just species life history information and patterns of habitat use. In order to fully assess how different techniques of dredging could affect fishery resources, site-specific investigations of physical environmental processes are recommended. Information needs for EFH analyses ideally include assessment of the level of importance of geomorphological and hydrodynamic flow regimes with respect to fishery resources.

Information on these physical environmental parameters can facilitate analysis of sand mining effects on sediment transport and microcirculation patterns, which greatly influence patterns of benthic community structure. When designing sand mining projects, information is needed regarding significance of local and regional current patterns to benthic trophics and secondary production, temporal production cycles, and reproduction and larval dispersal patterns.

Biological productivity is affected by location across ridge and shoal systems, and a spatial examination may determine if different locations vary in EFH function. Many of the benthic invertebrates inhabiting potential shoal mining sites are potential prey for fishes; however, forage items and biomass are not distributed evenly. Important fishery resources inhabit shoal systems and utilize physically dynamic microhabitats and benthic food items, both of which are related to the ambient hydrodynamic flow regime and its related parameters of bathymetry and sedimentary habitat. Shoal crests tend to support less diverse invertebrate assemblages than those found on the surrounding seafloor. The crests also in general lack bioengineered structures at the sediment-water interface, which tend to attract more diverse benthic assemblages than occur in nonstructured substrata. In formulating analyses of mining impacts on EFH, spatial and temporal variability in resource and stressor distributions should be evaluated.

Many harvested species that can use shoals are subject to management via EFH or catch-based fishery regulations, are opportunistic in space use (Able et al., 2006) and are making long-distance migrations across a wide shelf every 6 months between diverse end points (shallow estuaries and deep OCS habitats). These species and species groups include striped bass, bluefish, mackerel species, flounder species, croaker species (sciaenids), and squid species. Temporal changes in faunal distributions are, therefore, very important in EFH analyses due to transient use of shoals and ridges by both demersal and pelagic species and life stages. The available information for two flounder species and two water-column species (bay anchovy and striped bass) were examined in terms of distribution and abundance across the shelf by habitat, cross-shelf physiographic gradient, and seasonal scales. The use of sedimentary and other habitats within shoal areas of the inner OCS suggests that both bottom and water-column fishes are often spatially opportunistic in terms of habitat use and cross-shelf positioning, though temporally dependent on two annual cross-shelf migrations (e.g., Able et al., 2006; Sackett et al., 2007). This results in temporally variable EFH values for shoals, with the fall and winter as the periods of greatest habitat value for most demersal and water-column fishes that undergo seasonal cross-shelf migrations. Able et al. (2006) have found that inner shelf fish species typically settle in estuaries or the ocean, or estuaries only, not in the ocean only. It appears that the majority of the estuary and ocean settlers settle more abundantly in ocean than estuarine areas. The role of shoals as potential settlement habitat remains not well known for many species.

8.0 LITERATURE CITED

Abele, L.G. and K. Walters. 1979. Marine benthic diversity: A critique and alternative explanation. J. Biogeogr. 6:115-126.

Abelson, A. and M. Denny. 1997. Settlement of marine organisms in flow. Annu. Rev. Ecol. Syst. 28:317-339.

Able, K.W. 2005. A reexamination of fish estuarine dependence: Evidence for connectivity between estuarine and ocean habitats. Est. Coast. Shelf Sci. 64:5-17.

Able, K.W. and M.P. Fahay. 1998. The First Year of Life in Estuarine Fishes of the Mid-Atlantic Bight. Rutgers Univ. Press. 342 pp.

Able, K.W. and T.M. Grothues. 2007. Diversity of estuarine movements of striped bass (*Morone saxatilis*): A synoptic examination of an estuarine system in southern New Jersey. Fish. Bull. 105:426-435.

Able, K.W. and S.M. Hagan. 1995. Fishes in the vicinity of Beach Haven Ridge: Annual and seasonal patterns of abundance during the early 1970s. IMCS Technical Report 95-24. Institute of Marine and Coastal Sciences, Rutgers University, New Jersey. 36 pp.

Able, K.W. and S.C. Kaiser. 1994. Synthesis of summer flounder habitat parameters. NOAA Coastal Ocean Program Decision Analysis Series No. 1. NOAA Coastal Ocean Office. Silver Spring, MD. 68 pp.

Able, K.W., R.E. Matheson, W.W. Morse, M.P. Fahay, and G.P. Shepherd. 1990. Patterns of summer flounder (*Paralichthys dentatus*) early life history in the Mid-Atlantic Bight and New Jersey estuaries. Fish. Bull. 88(1):1-12.

Able, K.W., M.P. Fahay, and G.R. Shepherd. 1995. Early life history of black sea bass, *Centropristis striata*, in the mid-Atlantic Bight and a New Jersey estuary. Fish. Bull. 93:429-445.

Able, K.W., M.P. Fahay, D.A. Witting, R.S. McBride, and S.M. Hagan. 2006. Fish settlement in the ocean vs. estuary: Comparison of pelagic larval and settled juvenile composition and abundance from southern New Jersey, USA. Est. Coast. Shelf Sci. 66:280-290.

Able, K.W., J.H. Balletto, S.M. Hagan, P.R. Jivoff, and K. Strait. 2007. Linkages between salt marshes and other nekton habitats in Delaware Bay, USA. Rev. Fish. Sci. 15:1-61.

Aguilar, R., A.H. Hines, M.A. Kramer, T.G. Wolcott, and R. Lipcius. 2005. Timing and route of movement and migration of post-copulatory female blue crabs, *Callinectes sapidus* Rathbun, from the upper Chesapeake Bay. J. Exp. Mar. Biol. Ecol. 319:117-128.

Allen, J.D. and B. Pernet. 2007. Intermediate modes of larval development: Bridging the gap between planktotrophy and lecithotrophy. Evol. Dev. 9:643-653.

Andrew, N.L. and B.D. Mapstone. 1987. Sampling and the description of spatial pattern in marine ecology. Oceanogr. Mar. Biol. Annu. Rev. 25:39-90.

Arendt, M.D., J.E. Olney, and J.A. Lucy. 2001. Stomach content analysis of cobia, *Rachycentron canadum*, from lower Chesapeake Bay. Fish. Bull. 99:665-670.

Ault, J.S., G.A. Diaz, S.G. Smith, J. Luo, and J.E. Serafy. 1999. An efficient sampling survey design to estimate pink shrimp population abundance in Biscayne Bay, Florida. N. Amer. J. Fish. Manage. 19:696–712.

Auster, P.J. 1987. The effect of current speed on the small scale spatial distribution of fishes. Symposia Series for Undersea Research 2(2):7-16. National Oceanic and Atmospheric Administration, Office of Undersea Research, Rockville, MD.

Auster, P.J., R.J Malatesta, S.C. LaRosa, R.A. Cooper, and L.L. Stewart. 1991. Microhabitat utilization by the megafaunal assemblage at a low relief outer continental shelf site - Middle Atlantic Bight, USA. J. Northw. Atl. Fish. Sci. 11:59-69.

Auster, P.J., R.J. Malatesta, and S.C. LaRosa. 1995. Patterns of microhabitat utilization by mobile megafauna on the southern New England (USA) continental shelf and slope. Mar. Ecol. Prog. Ser. 127:77-85.

Auster, P.J., J. Lindholm, S. Schaub, G. Funnell, L.S. Kaufman, and P.C. Valentine. 2003. Use of sand wave habitats by silver hake. J. Fish Bio. 62:143-152.

Baird, D. and R.E. Ulanowicz. 1989. The seasonal dynamics of the Chesapeake Bay ecosystem. Ecol. Monogr. 59:329-364.

Barnes, R.D. 1980. Invertebrate Zoology, Fourth Edition. W.B. Saunders College, Philadelphia, PA.

Barros, F., A.J. Underwood, and P. Archambault. 2004. The influence of troughs and crests of ripple marks on the structure of subtidal benthic assemblages around rocky reefs. Estuar. Coast. Shelf Sci. 60:781-790.

Barry A. Vittor & Associates, Inc. 1999. Pre- and post-dredging monitoring of macroinvertebrate assemblages at a borrow area located offshore of Coney Island, New York: 1992-1998 Data Synthesis. U.S. Army Corps of Engineers, New York District, 10 pp. + app.

Battjes, J.A. and J.P. Janssen. 1978. Energy loss and set-up due to breaking of random waves, pp. 569-587. Proceedings of the 23rd International Conference on Coastal Engineering, American Society Civil Engineers, NY. .

Beardsley, R.C. and C.D. Winant. 1979. On the mean circulation in the Mid-Atlantic Bight. J. Phys. Oceanogr. 9:612-619.

Bertram, D.F. and W.C. Leggett. 1994. Predation risk during the early life history periods of fishes: Separating the effects of size and age. Mar. Ecol. Prog. Ser. 109:105-114.

Beukema, J.J., E.C. Flach, R. Dekker, and M. Starink. 1999. A long-term study of the recovery of the macrozoobenthos on large defaunated plots on a tidal flat in the Wadden Sea. J. Sea Res. 42:235-254.

Bhaud, M. 1998. The spreading potential of polychaete larvae does not predict adult distributions; consequences for conditions of recruitment. Hydrobiol. 375-376:35-47.

Biggs, R.B. 1968. Environmental effects of overboard spoil disposal, pp. 477-478. J. Sanit. Eng. Div. 94, Number SA3, Proceeding Paper 5979.

Boesch, D.F. 1972. Species diversity of marine macrobenthos in the Virginia area. Chesapeake Sci. 13:206-211.

Boesch, D.F. 1979. Benthic ecological studies: Macrobenthos. Chapter 6. In: Middle Atlantic Outer Continental Shelf Environmental Studies. Final Report to Bureau of Land Management. Virginia Institute of Marine Science, Gloucester Point, VA.

Borthagaray, A. and A. Carranza. 2007. Mussels as ecosystem engineers: Their contribution to species richness in a rocky littoral community. Acta Oecologia 31:243-250.

Bowman, R.E., C.E. Stillwell, W.L. Michaels, and M.D. Grosslein. 2000. Food of northwest Atlantic fishes and two common species of squid. U.S. Department of Commerce, NOAA Tech Memo NMFS NE 155. 137 pp.

Boyd, S.E., D.S. Limpenny, H.L. Rees, and K.M. Cooper. 2005. The effects of marine sand and gravel extraction on the macrobenthos at a commercial dredging site (results 6 years post-dredging). ICES J. Mar. Sci. 62:145-162.

Bray, J.R. and J.T. Curtis. 1957. An ordination of the upland forest communities of southern Wisconsin. Ecol. Monogr. 27:325-349.

Brookins, K.G. and C.E. Epifanio. 1985. Abundance of brachyuran larvae in a small coastal inlet over six consecutive tidal cycles. Estuaries 8:80-87.

Brooks, R.A., C.N. Purdy, S.S. Bell, and K.J. Sulak. 2006. The benthic community of the eastern U.S. continental shelf: A literature synopsis of benthic faunal resources. Cont. Shelf Res. 26:804-818.

Bumpus, D.F. 1973. A description of the circulation on the continental shelf of the east coast of the U.S. Prog. Oceanogr. 6:111-157.

Burlas, M., G.L. Ray, and D. Clarke. 2001. The New York District's Biological Monitoring Program for the Atlantic Cost of New Jersey, Asbury Park to Manasquan Section Beach Erosion Control Project, Final Report. U.S. Army Corps of Engineers, New York District, Engineer Research and Development Center and Waterways Experiment Station.

Butman, C.A. 1987. Larval settlement of soft-sediment invertebrates: the spatial scales of pattern explained by active habitat selection and the emerging role of hydrodynamic processes. Oceanogr. Mar. Biol. Annu. Rev. 25:113-165.

Butman, C.A., J.P. Grassle, and C.M. Webb. 1988. Substrate choices made by marine larvae settling in still water and in a flume flow. Nature 333:771-773.

Buttolph, A.M., C.W. Reed, N.C. Kraus, N. Ono, M. Larson, B. Camenen, H. Hanson, T. Wamsley, and A.K. Zundel. 2006. Two-dimensional depth-averaged circulation model CMS-M2D: Version 3.0, Report 2: Sediment transport and morphology change. Coastal and Hydraulics Laboratory Engineering Technical Note ERDC/CHL CHETN-IV-50. U.S. Army Engineer Research and Development Center, Vicksburg, MS. Report ERDC/CHL-TR-06-7. <http://cirp.wes.army.mil/cirp/cetns/chetn-iv50.pdf>

Byrnes, M.R. and C.G. Groat. 1992. Characterization of the development potential of Ship Shoal sand for beach replenishment of the Isles Dernieres: An introduction, pp. 75-78. 12th Annual Information Transfer Meeting, U.S. Minerals Management Service, New Orleans, LA.

Byrnes, M.R., R.M. Hammer, B.A. Vittor, J.S. Ramsey, D.B. Snyder, K.F. Bosma, J.D. Wood, T.D. Thibaut, N.W. Phillips. 1999. Environmental survey of identified sand resource areas offshore Alabama: Volume I: Main Text, Volume II: Appendices. U.S. Department of Interior, Minerals Management Service, International Activities and Marine Minerals Division (INTERMAR), Herndon, VA. OCS Report MMS 99-0052, 326 pp. + 132 pp. appendices.

Byrnes, M.R., R.M. Hammer, B.A. Vittor, J.S. Ramsey, D.B. Snyder, K.F. Bosma, J.D. Wood, T.D. Thibaut, and N.W. Phillips. 2000. Environmental survey of potential sand resource sites offshore New Jersey. U.S. Department of the Interior, Minerals Management Service, International Activities and Marine Minerals Division (INTERMAR), Herndon, VA. OCS Report MMS 2000-052. 380 pp. + apps.

Byrnes, M.R., R.M. Hammer, B.A. Vittor, S.W. Kelley, D.B. Snyder, J.M. Cote, J.S. Ramsey, T.D. Thibaut, N.W. Phillips, and J.D. Wood. 2003. Collection of environmental data within sand resource areas offshore North Carolina and the environmental implications of sand removal for coastal and beach restoration. U.S. Department of the Interior, Minerals Management Service, Leasing Division, Sand and Gravel Unit, Herndon, VA. OCS Report MMS 2000-056. 256 pp. + apps.

Byrnes, M.R., R.M. Hammer, and T.D. Thibaut. 2004. Physical and biological effects of sand mining offshore Alabama. J. Coast. Res. 20(1):6-24.

Camp, D.K., N.H. Whiting, and R.E. Martin. 1977. Nearshore Marine Ecology at Hutchinson Island, Florida: 1971-1974, V. Arthropods. Flor. Mar. Res. Pub. 25.

Campbell, B.C. and K.W. Able. 1998. Life history characteristics of the northern pipefish, *Syngnathus fuscus*, in southern New Jersey. Estuaries 21(3):470-475.

Carr, S.D., R.A. Tankersley, J.L. Hench, R.B. Forward, Jr. and R.A. Luettich, Jr. 2004. Movement patterns and trajectories of ovigerous blue crabs *Callinectes sapidus* during the spawning migration. Estuar. Coast. Shelf Sci. 60:567-579.

Centre for Cold Ocean Resources Engineering. 1995. Proposed marine mining technologies and mitigation techniques: A detailed analysis with respect to the mining of specific offshore mineral commodities. U.S. Department of the Interior, Minerals Management Service, Office of International Activities and Marine Minerals, OCS Report MMS 95-0003, C-CORE Publication 96-C15. 280 pp. + apps.

Chapman, D.C. and R.C. Beardsley. 1989. On the origin of shelf water in the Middle Atlantic Bight. J. Phys. Oceanogr. 19:384-391.

Chia, F.S., J. Buckland-Nicks, and C.M. Young. 1984. Locomotion of marine invertebrate larvae: A review. Can. J. Zoo. 62:1,205-1,222.

Clancy, M. and C.E. Epifanio. 1988. Distribution of crab larvae in relation to tidal fronts in Delaware Bay, USA. Mar. Ecol. Prog. Ser. 57:77-82.

Clarke, K.R. and R.N. Gorely. 2001. Primer v5: User Manual/Tutorial PRIMER-E. Plymouth, United Kingdom.

Coastline Surveys Limited. 1998. Marine aggregate mining benthic and surface plume study. U.S. Department of the Interior, Minerals Management Service, Office of International Activities and Marine Minerals, Plume Research Group Report 98/555/03. 168 pp.

Cocito, S. 2006. Bioconstruction and biodiversity: Their mutual influence. Scientia Marina 68:137-144.

Collie, J.S., S.J. Hall, M.J. Kaiser, and I.R. Poiner. 2000. A quantitative analysis of fishing impacts on shelf-sea benthos. J. Anim. Ecol. 69:785-798.

Colton, J.B., Jr., W.G. Smith, A.W. Kendall, Jr., P.L. Berrien, and M.P. Fahay. 1979. Principal spawning areas and times of marine fishes, Cape Sable to Cape Hatteras. Fish. Bull. 76:911-915.

Colvocoresses, J.A. and J.A. Musick. 1984. Species associations and community composition of Middle Atlantic Bight continental shelf demersal fishes. Fish Bull. 82:295-313.

Conkwright, R.D. and C.P. William. 1996. Offshore sand resources in central Maryland shoal fields. Maryland Geological Survey File Report No. 96-3, Baltimore, MD. 57 pp.

Conkwright, R.D., C.P.Williams, and L.B. Christiansen. 2000. Offshore sand resources in northern Maryland shoal fields. Maryland Geological Survey File Report No. 00-2, Baltimore, MD. 94 pp.

Cowen, R.K., J.A. Hare, and M.P. Fahay. 1993. Beyond hydrography: Can physical processes explain larval fish assemblages within the Middle Atlantic Bight? Bull. Mar. Sci. 53(2):567-587.

Crimaldi, J.P., J.K. Thompson, J.H. Rosman, R.J. Lowe, and J.R. Koseff. 2002. Hydrodynamics of larval settlement: The influence of turbulent stress events at potential recruitment sites. Limnol. Oceanogr. 47:1,137-1,151.

Cronin, E.L., R.B. Biggs, D.A. Flemer, G.T. Pfitzmeyer, F. Goodwin, Jr., W.L. Dovel, and D.E. Richie, Jr. 1970. Gross physical and biological effects of overboard spoil disposal in Upper Chesapeake Bay. University of Maryland, Chesapeake Biological Laboratory, Natural Resources Institute Special Report Number 3. 66 pp.

Cummings, V.J., R.D. Pridmore, S.F. Thrush, and J.E. Hewitt. 1995. Post-settlement movement by intertidal benthic macroinvertebrates: Do common New Zealand species drift in the water column? New Zealand J. Mar. Fresh. Res. 29:59-67.

Cutter, G.R. Jr., R.J. Diaz, J.A. Musick, J. Olney, Sr., D.M. Bilkovic, J.P.-Y. Maa, S.-C. Kim, C.S. Hardaway, Jr., D.A. Milligan, R. Brindley, and C.H. Hobbs, III. 2000. Environmental survey of potential sand resource sites offshore Delaware and Maryland. Final Report. Prepared by the Virginia Institute of Marine Science, College of William and Mary. U.S. Department of the Interior, Minerals Management Service, International Activities and Marine Minerals Division, Herndon, VA. OCS Study 2000-055.

Day, J.H., J.G. Field, and M.P. Montgomery. 1971. The use of numerical methods to determine the distribution of the benthic fauna across the continental shelf of North Carolina. J. Anim. Ecol. 40:93-125.

DeGoursey, R.E. and P.J. Auster. 1992. A mating aggregation of the spider crab (*Libinia emarginata*). J. Northw. Atl. Fish. Sci. 13:77–82.

Dernie, K.M., M.J. Kaiser, and R.M. Warwick. 2003. Recovery rates of benthic communities following physical disturbance. J. Anim. Ecol. 72:1,043-1,056.

DeVries, M.C., R.A. Tankersley, R.B. Forward, Jr., W.W. Kirby-Smith, and R.A. Luettich, Jr. 1994. Abundance of estuarine crab larvae is associated with tidal hydrologic variables. Mar. Biol. 118:403-413.

Diaz, R.J., G.R. Cutter, and K.W. Able. 2003. The importance of physical and biogenic structure to juvenile fishes on the shallow intercontinental shelf. Estuar. Coasts 26:12-20.

Diaz, R.J., G.R. Cutter, Jr., and C.H. Hobbs, III. 2004. Potential impacts of sand mining offshore of Maryland and Delaware: Part 2–Biological considerations. J. Coast. Res. 20(1):61-69.

Dietl, G.P. and R.R. Alexander. 1997. Predator-prey interactions between the naticids *Euspira heros* (Say) and *Neverita duplicata* (Say) and the Atlantic surfclam *Spisula solidissima* (Dillwyn) from Long Island to Delaware. J. Shellfish Res. 16 413-422.

Dittel, A.I. and C.E. Epifanio. 1982. Seasonal abundance and vertical distribution of crab larvae in Delaware Bay. Estuaries 5:197-202.

Dobrzynski, T. and K. Johnson. 2001. Regional Council approaches to the identification and protection of habitat areas of particular concern. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Office of Habitat Conservation, Silver Spring, MD.

Drake, P., A. Arias, and M. Rodríguez. 1998. Seasonal and tidal abundance patterns of decapod crustacean larvae in a shallow inlet (SW Spain). J. Plankton Res. 20:585-601.

Drucker, B.S., W. Waskes, and M.R. Byrnes. 2004. The U.S. Minerals Management Service Outer Continental Shelf Sand and Gravel Program: Environmental studies to assess the potential effects of offshore dredging operations in Federal waters. J. Coast. Res. 20(1):1-5.

Duane, D.B., M.E. Field, E.P. Meisburger, D.J.P. Swift, and S.J. Williams. 1972. Linear shoals on the Atlantic inner continental shelf, Florida to Long Island, pp. 447-498. In: D.J.P. Swift, D.B. Duane, and O.H. Pilkey (eds.), Shelf Sediment Transport: Process and Pattern. Dowden, Hutchinson, and Ross, Stroudsburg, PA.

Duchêne, J.C. 2004. Early recognition of sediment during settlement of *Eupolymnia nebulosa* (Polychaeta: Terebellidae) larvae. Mar. Biol. 145:79-85.

Dunne, J.A., R.J. Williams, N.D. Martinez. 2004. Network structure and robustness of marine food webs. Mar. Ecol. Prog. Ser. 273:291–302.

Duval, E.J. and K.W. Able. 1998. Aspects of the life history of the seaboard goby, *Gobiosoma ginsburgi*, in estuarine and inner continental shelf waters. Bull. New Jersey Acad. Sci. 43(1):5-10.

Eckman, J.E. 1996. Closing the larval loop: Linking larval ecology to the population dynamics of marine benthic invertebrates. J. Exper. Mar. Biol. Ecol. 200:207-237.

Eckman, J.E., W.B. Savidge, and T.F. Gross. 1990. Relationship between duration of cyprid attachment and drag forces associated with detachment of *Balanus amphitrite* cyprids. Mar. Biol. 107:111-118.

Eklund, A. and T.E. Targett. 1991. Seasonality of fish catch rates and species composition from the hard bottom trap fishery in the Middle Atlantic Bight (US east coast). Fish. Res. 12(1):1-22**.**

Engstrom, S.J. and R.L. Marinelli. 2005. Recruitment responses of benthic infauna to manipulated sediment geochemical properties in natural flows. J. Mar. Res. 63:407-436.

Epifanio, C.E. 1988. Dispersal strategies of two species of swimming crab on the continental shelf adjacent to Delaware Bay. Mar. Ecol. Prog. Ser. 49:243-248.

Epifanio, C.E. and R.W. Garvine. 2001. Larval transport on the Atlantic Continental Shelf of North America: A review. Est. Coast. Shelf Sci. 52:51-77.

Eriksson, B.K., A. Rubach, and H. Hillebrand. 2006. Biotic habitat complexity controls species diversity and nutrient effects on net biomass production. Ecology 87:246–254.

Fay, C.W., R.J. Neves, and G.B. Pardue. 1983. Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (Mid-Atlantic): Surf clam. U.S. Fish and Wildlife Service, Division of Biological Services, FWS/OBS-82/11.13. 23 pp.

Fenchel, T. 1969. The ecology of marine microbenthos IV. Structure and function of the benthic ecosystem, its chemical and physical factors and the microfauna communities with special reference to the ciliated protozoa. Ophelia 6:1-182.

Field, M.E. 1980. Sand bodies on coastal plain shelves; Holocene record of the U.S. Atlantic inner shelf of Maryland. J. Sed. Petrol. 50:505-528.

Field, M.E. and D.B. Duane. 1976. Post Pleistocene history of the United States inner continental shelf: Significance to the origin of barrier islands. Geol. Soc. Am. Bull. 87:691-702.

Flint, R.W. and J.S. Holland. 1980. Benthic infaunal variability on a transect in the Gulf of Mexico. University of Texas Marine Science Institute Contribution No. 328. Academic Press, London. 14 pp.

Forster, S. and G. Graf. 1995. Impact of irrigation flux into the sediment: intermittent pumping by *Callianassa subterranean* and “piston-pumping” by *Lanice conchilega.* Mar. Biol. 123:335-346.

Forward, R.B., Jr., J. Swanson, and R.A. Tankersely. 1997. Endogenous swimming rhythms of blue crab, *Callinectes sapidus*, Megalopae: Effects of offshore and estuarine cues. Mar. Biol. 127:621-628.

Franz, D.R. 1977. Size and age-specific predation by *Lunatia heros* (Say, 1822) on the surf clam *Spisula solidissima* (Dillwyn, 1817) off western Long Island, New York. Veliger 20:144-150.

Gabriel, W.L. 1992. Persistence of demersal fish assemblages between Cape Hatteras and Nova Scotia, Northwest Atlantic. J. Northw. Atl. Fish. Sci. 14:29-46.

Garrison, L.P. 1999. Vertical migration behavior and larval transport in brachyuran crabs. Mar. Ecol. Prog. Ser. 176:103-113.

Garrison, L.P. and J.S. Link. 2000. Dietary guild structure of the fish community in the northeast United States continental shelf ecosystem. Mar. Ecol. Prog. Ser. 202:231-240.

Garvine, R.W. 1987. Observations of the coupled circulation between Delaware Bay and Inner continental shelf. Eos Trans. Am. Geophys. Union 68:17-33.

Giangrande, A., S. Geraci, and G. Belmonte. 1994. Life-cycle and life-history diversity in marine invertebrates and the implications in community dynamics. Oceanogr. Mar. Biol. Annu. Rev. 32:305-333.

Gibson, G.D. and A.J.F. Gibson. 2004. Heterochrony and the evolution of poecilogony: Generating larval diversity. Evolution 58:2,704-2,717.

Goda, Y. 1985. Random Seas and Design of Maritime Structures. University of Tokyo Press, Tokyo, Japan.

Gosselin, L.A. and P. Qian. 1997. Juvenile mortality in marine benthic invertebrates. Mar. Ecol. Prog. Ser. 146:265-282.

Grabowski, J.H. and S.P. Powers. 2004. Habitat complexity mitigates trophic transfer on oyster reefs. Mar. Ecol. Prog. Ser. 277:291-295.

Graff, G. 1992. Benthic-pelagic coupling: A benthic view. Oceanogr. Mar. Biol. Annu. Rev. 30:149-190.

Grantham, B.A., G.L. Eckert, and A.L. Shanks. 2003. Dispersal potential of marine invertebrates in diverse habitats. Ecol. Applic. 13 (Supplement):108-116.

Gross, T.F., F.E. Werner, and J.E. Eckman. 1992. Numerical modeling of larval settlement in turbulent bottom boundary layers. J. Mar. Res. 50:611-642.

Grosslein, M.D. and T.R. Azarovitz. 1982. Fish distribution, pp. 182. In: MESA New York Bight Atlas Monograph 15. New York Sea Grant Institute.

Grove, R.S., M. Nakamura, and C.J. Sonu. 1991. Design and engineering of manufactured habitats for fisheries enhancement, pp. 109-152. In: W. Seaman and L. Sprague (eds.), Artificial Habitats for Marine and Freshwater Fisheries. Academic Press, New York, NY. 285 pp.

Günther, C. 1992. Dispersal of intertidal invertebrates: A strategy to react to disturbances of different scales? Netherlands J. Sea Res. 30:45-56.

Hadfield, M.G., E.J. Carpizo-Ituarte, K. del Carmen, and B.T. Nedved. 2001. Metamorphic competence, a major adaptive convergence in marine invertebrate larvae. Am. Zool. 41:1,123-1,131.

Haefner, P.A., Jr. 1976. Distribution, reproduction and moulting of the rock crab, *Cancer irroratus* Say, 1917, in the mid-Atlantic Bight. J. Nat. Hist. 10:377-379.

Haefner, P.A., Jr. 1979. Comparative review of the biology of north Atlantic caridean shrimps (*Crangon*), with emphasis on *C. septemspinosa*. Bull. Biol. Soc. Wash. 3:1-40.

Haefner, P.A., Jr., and W.A. Van Engel. 1975. Aspects of molting, growth and survival of male rock crabs, *Cancer irroratus*, in Chesapeake Bay. Chesapeake Sci. 16:253-265.

Hales, L.S., Jr. and K.W. Able. 2001. Winter mortality, growth, and behavior of young-of-the-year of four coastal marine fishes in New Jersey (USA) waters. Mar. Biol. 139:45-54.

Hall, S.J. 1994. Physical disturbance and marine benthic communities: Life in unconsolidated sediment. Oceanogr. Mar. Biol. Annu. Rev. 32:179-239.

Hall, S.J., D.J. Basford, M.R. Robinson, D.G. Raffaelli, and I. Tuck. 1991. Patterns of recolonisation and the importance of pit-digging by the edible crab *Cancer pagurus* in a subtidal sand habitat. Mar. Ecol. Prog. Ser. 72:93-102.

Hall, S.J., D. Raffaelli, and S.F. Thrush. 1994. Patchiness and disturbance in shallow water benthic assemblages, pp. 333-375. In: A.G. Hildrew, P.S. Giller, and D. Raffaelli, (eds.), Aquatic Ecology: Scale, Pattern, and Processes. Blackwell Scientific, Oxford, UK.

Hammer, R.M., M.R. Byrnes, D.B. Snyder, T.D. Thibaut, J.L. Baker, S.W. Kelley, J.M. Cote, L.M. Lagera, S.T. Viada, B.A. Vittor, J.S. Ramsey, and J.D. Wood. 2005. Environmental surveys of potential borrow areas on the central East Florida Shelf and the environmental implications of sand removal for coastal and beach restoration. U.S. Department of the Interior, Minerals Management Service, Leasing Division, Marine Minerals Branch, Herndon, VA. OCS Report MMS 2004-037. 328 pp. + apps.

Hanson, R.B., K.R. Tenore, S. Bishop, C. Chamberlain, M.M. Pamatmat, and J. Tietjen. 1979. Benthic enrichment in the Georgia Bight related to Gulf Stream intrusions and estuarine outwelling. J. Mar. Res. 39:417-441.

Hare, J.A. and K.W. Able. 2007. Mechanistic links between climate and fisheries along the east coast of the United States: explaining population outbursts of Atlantic croaker (*Micropogonias undulatus*). Fish. Oceanogr. 16(1):31-45.

Hare, J.A. and R.K. Cowen. 1996. Transport mechanisms of larval and pelagic juvenile bluefish (*Pomatomus saltatrix*) from South Atlantic Bight spawning grounds to Middle Atlantic Bight nursery habitats. Limnol. Oceanogr. 41:1,264-1,280.

Hayes, M.O. and R.B. Nairn. 2004. Natural maintenance of sand ridges and linear shoals on the U.S. Gulf and Atlantic Continental Shelves and the potential impacts of dredging. J. Coast. Res. 20(1):138-148.

Hazlett, B.A., P. Acquistapace, and F. Gherardi. 2006. Responses of the crayfish *Orconectes virilis* to chemical cues depend upon flow conditions. J. Crust. Biol., 26(1):94-98.

Heck, K.L., Jr. and T.A. Thoman. 1984. The nursery role of seagrass meadows in the upper and lower reaches of the Chesapeake Bay. Estuaries 7:70-92.

Heck, K.L. and G.S. Wetstone. 1977. Habitat complexity and invertebrate species richness and abundance in tropical seagrass meadows. J. Biogeogr. 4:135-142.

Heck, L., Jr, L.D. Coen, and S.G. Morgan. 2001. Pre- and post-settlement factors as determinants of juvenile blue crab *Callinectes sapidus* abundance: Results from north-central Gulf of Mexico. Mar. Ecol. Prog. Ser. 222:163-176.

Hedvall, O., P. Moksnes, and L. Pihl. 1989. Active habitat selection by megalopae and juvenile shore crabs *Carcinus maenas*: A laboratory study in an annular flume. Hydrobiologia 375-376:89-100.

Hentschel, B.T. and B.S. Herrick. 2005. Growth rates of interface-feeding spionid polychaetes in simulated tidal currents. J. Mar. Res. 63:983-999.

Herbich, J.B. 1992. Handbook of Dredging Engineering. McGraw-Hill, Inc., New York, NY. 740 pp.

Herbich, J.B. and S.B. Brahme. 1991. Literature review and technical evaluation of sediment resuspension during dredging. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Contract Report HL-91-1.

Hines, A.H. 1986a. Larval patterns in the life histories of brachyuran crabs (Crustacea, Decapoda, Brachyura). Bull. Mar. Sci. 39:444-466.

Hines, A.H. 1986b. Larval problems and perspectives in life histories of marine invertebrates. Bull. Mar. Sci. 39:506-525.

Hongguang, M. and J.P. Grassle. 2004. Invertebrate larval availability during summer upwelling and downwelling on the inner continental shelf off New Jersey. J. Mar. Res. 62:837-865.

Howe, S., D. Maurer, and W. Leathem. 1988. Secondary production of benthic molluscs from the Delaware Bay and coastal area. Est. Coast. Shelf Sci. 26: 81-94.

Hrabovsky, L. 1990. Hydraulic Cutterhead Pipeline Dredging. In: D.D. Dickerson and D.A. Nelson (comps.), Proceedings of the National Workshop on Methods to Minimize Dredging Impacts on Sea Turtles, Jacksonville, FL, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Miscellaneous Paper EL-90-5. pp. 56-58.

Hubertz, J.M., R.M. Brooks, W.A. Brandon, and B.A. Tracy. 1993. Hindcast Wave Information for the U.S. Atlantic Coast. WIS Report 30, U.S. Army Engineer Waterways Experiment Station.

Hughes, T.P. and J.H. Connell. 1999. Multiple stressors on coral reefs: A long-term perspective. Limnol. Oceanogr. 44(3, Part 2):932-940.

Hulscher, S.J.M.H., H.E. De Swart, and H.J. De Vriend. 1993. The generation of offshore tidal sand banks and sand waves. Cont. Shelf. Res. 13:1,183-1,204.

Huthnance, J.M. 1982. On one mechanism forming linear sand banks. Est. Mar. Coast. Sci. 14:79–99.

Ingle, R.M. 1952. Studies on the Effect of Dredging Operations upon Fish and Shellfish. Florida State Board of Conservation, Technical Series 5. 26 pp.

Jacobi, C.M. and R. Langevin. 1996. Habitat geometry on benthic substrata: effects on arrival and settlement of mobile epifauna. J. Exper. Mar. Biol. Ecol. 206:39-54

Johnson, R.O. and W.G. Nelson. 1985. Biological effects of dredging in an offshore borrow area. Fla. Sci. 48:166-188.

Jones, C.G., J.H. Lawton, and M. Shachak. 1994. Organisms as ecosystems engineers. Oikos 69:373-386.

Jones, C.G., J.H. Lawton, and M. Shachak. 1997. Positive and negative effects of organisms as physical ecosystem engineers. Ecology 78:1,946-1,957.

Jones, G. and S. Candy. 1981. Effects of dredging on the macrobenthic infauna of Botany Bay. Aust. J. Mar. Fresh. Res. 32:379-399.

Jones, S.E. and C.F. Jago. 1993. In situ assessment of modification of sediment properties by burrowing invertebrates. Mar. Biol. 115:133-142.

Jonsson, P.R., C. André, and M. Lindegarth. 1991. Swimming behaviour of marine bivalve larvae in a flume boundary layer flow: Evidence for near-bottom confinement? Mar. Ecol. Prog. Ser. 79:67-76.

Jutte, P.C., R.F. Van Dolah, and P.T. Gayes. 2002. Recovery of benthic communities following offshore dredging, Myrtle Beach, South Carolina. Shore and Beach 70:25-30.

Kaiser, M.J., M. Bergmann, H. Hinz, M. Galanidi, R. Shucksmith, E.I.S. Rees, T. Darbyshire, and K. Ramsay. 2004. Demersal fish and epifauna associated with sandbank habitats. Estuar. Coast. Shelf Sci. 60:445-456.

Keddy, P.A. 1991. Working with heterogeneity: An operator's guide to environmental gradients. In: J. Kolasa and S.T.A. Pickett (eds.), Ecological Heterogeneity. Springer-Verlag, New York.

Kelley, S.W., J.S. Ramsey, and M.R. Byrnes. 2004. Evaluating the physical effects of offshore sand dredging for beach nourishment. J. Coast. Res. 20(1):89-100.

Kerr, S.J. 1995. Silt, turbidity and suspended sediments in the aquatic environment: An annotated bibliography and literature review. Ontario Ministry of Natural Resources, Southern Region Science and Technology Transfer Unit, Tech. Rep. TR-008. 277 pp.

Kingsford , M.J., J.M. Leis, A. Shanks, K.C. Lindeman, S.G. Morgan, and J. Pineda. 2002. Sensory environments, larval abilities and local self-recruitment. Bull. Mar. Sci. 70(1):309-340.

Kristensen, E., M.H. Jensen, and T.K. Andersen. 1985. The impact of polychaete (*Nereis virens* Sars) burrows on nitrification and nitrate reduction in estuarine sediments. J. Exper. Mar. Biol. Ecology 85:75-91.

LaSalle, M.W., D.G. Clarke, J. Homziak, J.D. Lunz, and T.J. Fredette, 1991. A Framework for Assessing the Need for Seasonal Restrictions on Dredging and Disposal Operations. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Tech. Rep. D-91-1. 74 pp.

Lazzari, M.A. and K.W. Able. 1990. Northern pipefish, *Syngnathus fuscus*, occurrences over the Mid-Atlantic Bight continental shelf: Evidence of seasonal migration. Env. Biol. Fish. 27:177-185.

Levin, L.A. 1984. Life history and dispersal patterns in a dense infaunal polychaete assemblage: community structure and response to disturbance. Ecology 65:1,185-1,200.

Levinton, J. and B. Kelaher. 2004. Opposing organizing forces of deposit-feeding marine communities. J. Exper. Mar. Biol. Ecol. 300:65-82.

Lindegarth, M., C. André, and P.R. Jonsson. 2002. Physical and numerical modelling of the role of hydrodynamic processes on adult-larval interactions of a suspension-feeding bivalve. J. Mar. Res. 60:499-516.

Lindeman, K.C., G.A. Diaz, J.E. Serafy, and J.S. Ault. 1998. A spatial framework for assessing cross-shelf habitat use among newly settled grunts and snappers. Proc. Gulf Caribb. Fish. Inst. 50:385-416.

Lindeman, K.C., R. Pugliese, G.T. Waugh, and J.S. Ault. 2000. Developmental patterns within a multispecies reef fishery: Management applications for essential fish habitats and protected areas. Bull. Mar. Sci. 66(3):929-956.

Lindeman, K.C., T.N. Lee, W.D. Wilson, R. Claro, and J.S. Ault. 2001. Transport of larvae originating in southwest Cuba and the Dry Tortugas: Evidence for partial retention in grunts and snappers. Proc. Gulf Caribb. Fish. Inst. 52:732-747.

Link, J. 2002. Does food web theory work for marine ecosystems? Mar. Ecol. Prog. Ser. 230:1-9.

Louis Berger Group. 1999. Use of Federal Offshore Sand Resources for Beach and Coastal Restoration in New Jersey, Maryland, Delaware, and Virginia. U.S. Department of the Interior, Minerals Management, OCS Study MMS 99-0036. 355 pp.

Luettich, R.A., Jr., J.J. Westerink, and N.W. Scheffner. 1992. ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Estuaries, Report 1: Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL. Dredging Research Program Technical Report DRP-92-6. U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS. 137 pp.

Lyons, W.G. 1989. Nearshore Marine Ecology at Hutchinson Island, Florida: 1971-1974. XI. Molluscs. Fla. Mar. Res. Pub. 47. 133 pp.

Maa, J.P.-Y., C.H. Hobbs, S.C. Kim, and E. Wei. 2004. Potential impacts of sand mining offshore of Maryland and Delaware: Part 1 - Impacts on physical oceanographic processes. J. Coast. Res. 20(1):44-60.

Mahon, R., S.K. Brown, K.C.T. Zwanenburg, D.B. Atkinson, K.B. Buja, L. Claflin, G.D. Howell, M.E. Monaco, R.N. O’Boyle, and M. Sinclair. 1998. Assemblages and biogeography of demersal fishes of the east coast of North America. Can. J. Fish. Aquat. Sci. 55:1,704-1,738.

Marinelli, R.L. and S.A. Woodin. 2002. Experimental evidence for linkages between infaunal recruitment, disturbance, and sediment surface chemistry. Limnol. Oceanogr. 47:221-229.

Marsh, G.A. and D.B. Turbeville. 1981. The environmental impact of beach nourishment: Two studies in southeastern Florida. Shore and Beach 1981:40-44.

Martino, E. and K.W. Able. 2003. Fish assemblages across the marine to low salinity transition zone of a temperate estuary. Est. Coast. Shelf Sci. 56(5-6):967-985.

Maurer, D., R.T. Keck, J.C. Tinsman, W.A. Leathem, C. Wethe, C. Lord, and T.M. Church. 1986. Vertical migration and mortality of marine benthos in dredged material: A synthesis. Internationale Revue der Gesamten Hydrobiologie 71:49-63.

Mayer, L.M., D.F. Schick, R.H. Findlay, and D.L. Rice. 1991. Effects of commercial dragging on sedimentary organic matter. Mar. Environ. Res. 31:249-261.

McBride, R.A. and M.R. Byrnes. 1995. Surficial sediments and morphology of the Southwestern Alabama/Western Florida panhandle coast and shelf. Gulf Coast Assoc. Geol. Soc. Trans. 45:393-404.

McBride, R.A. and T.F. Moslow. 1991. Origin, evolution, and distribution of shoreface sand ridges, Atlantic inner shelf, U.S.A. Mar. Geol. 97:57-85.

McBride, R.A., L.C. Anderson, A. Tudoran, and H.H. Roberts. 1999. Holocene stratigraphic architecture of a sand-rich shelf and the origin of linear shoals: Northeastern Gulf of Mexico, pp. 95-126. In: K.M. Bergman and J.W. Snedden (eds.), Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic Analysis and Sedimentologic Interpretation. Tulsa, Oklahoma: SEPM (Society for Sedimentary Geologists) Special Publication No. 64.

McBride, R.S. and K.W. Able. 1994. Reproductive seasonality, distribution, and abundance of *Prionotus carolinus* and *P. evolans* (Pisces: Triglidae) in the New York Bight. Est. Coast. Shelf Sci. 38:173-188.

McBride, R.S. and K.W. Able. 1998. Ecology and fate of butterflyfishes, *Chaetodon* spp., in the temperate, Western North Atlantic. Bull. Mar. Sci. 63(2):401-416.

McBride, R.S., J.B. O'Gorman and K.W. Able. 1998. Interspecific comparisons of searobin (*Prionotus* spp.) movements, size structure, and abundance in the temperate western North Atlantic. Fish. Bull. 96(2):303-314.

McCaully, J.E., R.A. Parr, and D.R. Hancock. 1977. Benthic infauna and maintenance dredging: A case study. Water Res. 11:233-242.

McConaugha, J.R. 1992. Decapod larvae: dispersal, mortality, and ecology. A working hypothesis. Am. Zool. 32:512-523.

Meyer, T.L., R.A. Cooper, and K.J. Pecci. 1981. The performance and environmental effects of a hydraulic clam dredge. Mar. Fish. Rev. 43:14-22.

Michel, J., R. Nairn, C.H. Peterson, S.W. Ross, R. Weisberg, and R. Randall. 2007. Critical technical review and evaluation of site-specific studies techniques for the MMS Marine Minerals Program. Minerals Management Service, MMS OCS Report 2007-047. 47 pp. + apps.

Mid-Atlantic Fishery Management Council. 1998a. Amendment 12 to the Summer Flounder, Scup, and Black Sea Bass Fishery Management Plan. Mid-Atlantic Fishery Management Council, Dover, DE. 398 pp. + apps.

Mid-Atlantic Fishery Management Council. 1998b. Amendment 1 to the Bluefish Fishery Management Plan. Mid-Atlantic Fishery Management Council, 2 Vols., Dover, DE. 341 pp. + apps.

Mileikovsky, S.A. 1973. Speed of active movement of pelagic larvae of marine bottom invertebrates and their ability to regulate their vertical position. Mar. Biol. 23:11-17.

Milstein, C.B. 1981. Abundance and distribution of juvenile *Alosa* species off southern New Jersey. Trans. Am. Fish. Soc. 110:306-309.

Milstein, C.B. and D.L. Thomas. 1976. Fishes new or uncommon to the New Jersey coast. Chesapeake Sci. 17(3):198-204.

Milstein, C.B. and D.L. Thomas. 1977. Summary of ecological studies for 1972-1975 in the bays and other waterways near Little Egg Inlet and in the ocean in the vicinity of the proposed site for the Atlantic generating station, New Jersey. Ichthyological Associates, Inc. Bulletin No. 18.

Minerals Management Service (MMS). 2003. Sand and gravel environmental studies within the Minerals Management Service: A framework for decisionmaking. U.S. Department of the Interior, Minerals Management Service, Offshore Minerals Management Leasing Division. Herndon, VA. 72 pp.

Modlin, R.F. 1962. The life cycle and recruitment of the sand shrimp, *Crangon septemspinosa*, in the Mystic River estuary, Connecticut. Estuar. Coasts 3:1-10.

Moore, J.C., E.L. Berlow, D.C. Coleman, P.C. de Ruiter, Q. Dong, A. Hastings, N.C. Johnson, K.S. McCann, K. Melville, P.J. Morin, K. Nadelhoffer, A.D. Rosemond, D.M. Post, J.L. Sabo, K.M. Scow, M.J. Vanni, and D.H. Wall. 2004. Detritus, trophic dynamics and biodiversity. Ecol. Lett. 7:584-600.

Moore, P.A., M.J. Weissburg, J.M. Parrish, R.K. Zimmer-Faust, and Greg A. Gerhardt. 1994. Spatial distribution of odors in simulated benthic boundary layer flows. J. Chem. Ecol. 20(2):211-222.

Moore, P.G. 1977. Inorganic particulate suspensions in the sea and their effects on marine animals. Oceanogr. Mar. Biol. Annu. Rev. 15:225-363.

Morrisey, D.J., L. Howitt, A.J. Underwood, and J.S. Stark. 1992. Spatial variation in soft-sediment benthos. Mar. Ecol. Prog. Ser. 81:197-204.

Morse, W.W. and K.W. Able. 1995. Distribution and life history of windowpane, *Scophthalmus aquosus*, off the northwestern United States. Fish. Bull. 93(4):675-693.

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

National Oceanic and Atmospheric Administration (NOAA). 2001. Sea level variations of the United States, 1854-1999. NOAA Technical Report NOS CO-OPS 36, Silver Spring, MD. 65 pp.

Natunewicz, C.C. and C.E. Epifanio. 2001. Spatial and temporal scales of patches of crab larvae in coastal waters. Mar. Ecol. Prog. Ser. 212:217-222.

Natunewicz, C.C., C.E. Epifanio, R.W. Garvine. 2001. Transport of crab larval patches in the coastal ocean. Mar. Ecol. Prog. Ser. 222:143-154.

Nelson, W.G. 1988. An overview of the effects of beach nourishment on the sand beach fauna, pp. 295-310. In: Proceedings of the 1988 National Conference on Beach Preservation Technology, Florida Shore and Beach Preservation Association, Tallahassee, FL.

Nelson, W.G. 1993. Beach restoration in the southeastern US: Environmental effects and biological monitoring. Ocean Coast. Mgmt. 19(1993):157-182.

Neuman, M.J. and K.W. Able. 1998. Experimental evidence of sediment preference by early life history stages of windowpane, (*Scophthalmus aquosus*). J. Sea Res. 40:33-41.

Neuman, M.J. and K.W. Able. 2002. Quantification of ontogenetic transitions during the early life of a flatfish, windowpane, *Scophthalmus aquosus* (Pleuronectiformes Scophthalmidae). Copeia 3:597-609.

Neuman, M.J., D.A. Witting, and K.W. Able. 2001. Relationships between otolith microstructure, otolith growth, somatic growth, and ontogenetic transition in two cohorts of windowpane. J. Fish Biol. 58:967-984.

Newcombe, C.P. and J.O.T. Jensen. 1996. Channel suspended sediment and fisheries: A synthesis for quantitative assessment of risk and impact. N. Am. J. Fish. Mgmt. 16(4):693-727.

Newell, R.C., L.J. Seiderer, and D.R. Hitchcock. 1998. The impact of dredging works in coastal waters: A review of the sensitivity to disturbance and subsequent recovery of biological resources on the seabed. Oceanogr. Mar. Biol. Annu. Rev. 36:127-178.

Newell, R.C., D.R. Hitchcock, and L.J. Seiderer. 1999. Organic enrichment associated with outwash from marine aggregates dredging: A probable explanation for surface sheens and enhanced benthic production in the vicinity of dredging operations. Mar. Poll. Bull. 38(9):808-818.

Nichols, M., R.J. Diaz, and L.C. Shaffner. 1990. Effects of hopper dredging and sediment dispersion, Chesapeake Bay. Environ. Geol. Water Sci. 15:31-43.

Nixon, S.W. and B.A. Buckley. 2002. A strikingly rich zone—nutrient enrichment and secondary production in coastal marine ecosystems. Estuaries 25:782-796.

Norkko, A., R. Rosenberg, S.F. Thrush, and R.B. Whitlatch. 2006. Scale- and intensity-dependent disturbance determines the magnitude of opportunistic response. J. Exper. Mar. Biol. Ecol. 330:195-207.

Nowell, A.R.M. and P.A. Jumars. 1984. Flow environments of aquatic benthos. Annu. Rev. Ecol. Syst. 15:303-28

Ólafsson, E.B., C.H. Peterson, and W.G. Ambrose Jr. 1994. Does recruitment limitation structure populations and communities of macro-invertebrates in marine soft sediments: The relative significance of pre- and post-settlement processes. Oceanogr. Mar. Biol. Annu. Rev. 32:65-109.

Oliver, J.S. and P.N. Slattery. 1985. Destruction and opportunity on the sea floor: Effects of gray whale feeding. Ecology 66:1,965-1,975.

Onuf, C.P. 1994. Seagrasses, dredging, and light in Laguna Madre, Texas, U.S.A. Est. Coast. Shelf Sci. 39:75-91.

Osenberg, C.W., B.M. Bolker, J.S. White, C. St. Mary, and J.S. Shima. 2006. Statistical issues and study design in ecological restorations: Lessons learned from marine reserves, pp. 280-302. In: D.A. Falk, M.A. Palmer, and J.B. Zedler (eds.), Foundations of Restoration Ecology. Island Press.

Osman, R.W. and R.B. Whitlatch. 1998. Local control of recruitment in an epifaunal community and the consequences to colonization processes. Hydrobiologia 375-376:113-123.

Overton, A.S., C.S. Manooch, III, J.W. Smith, K. Brennan. 2007. Interactions between adult migratory striped bass (*Morone saxatilis*) and their prey during winter off the Virginia and North Carolina coast from 1994 through 2007. Fish. Bull. 106:172-182.

Oviatt, C.A., C.D. Hunt, G.A. Vargo, and K.W. Kopchynski. 1982. Simulation of a storm event in a marine microcosm. J. Mar. Res. 39:605-618.

Palma, A.T., R.S. Steneck, and C.J. Wilson. 1999. Settlement-driven, multiscale demographic patterns of large benthic decapods in the Gulf of Maine. J. Exper. Mar. Biol. Ecol. 241:107-136.

Pana, S., N. MacDonald, J. Williams, B.A. O'Connor, J. Nicholson, and A.M. Davies. 2007. Modelling the hydrodynamics of offshore sandbanks. Cont. Shelf Res. 27:1,264-1,286.

Pardo, L.M., A.T. Palma, C. Prieto, P. Sepulveda, I. Valdivia, and F.P. Ojeda. 2007. Processes regulating early post-settlement habitat use in a subtidal assemblage of brachyuran decapods. J. Exper. Mar. Biol. Ecol. 344:10-22.

Parker, S.J., A.W. Shultz, and W.W. Schroeder. 1992. Sediment characteristics and seafloor topography of a palimset shelf, Mississippi-Alabama Continental Shelf, pp. 243-251. In: Quaternary Coasts of the United States: Lacustrine and Marine Systems. SEPM Special Publication 48.

Parker, S.J., D.J. Davies, and W.E. Smith. 1997. Geologic, economic, and environmental characterization of selected near-term leasable offshore sand deposits and competing onshore sources for beach nourishment. Geologic Survey of Alabama, Environmental Geology Division, Tuscaloosa, AL. Circular 190. 173 pp. + app.

Pawlik, J.R. 1992. Chemical ecology of the settlement of benthic marine invertebrates. Oceanogr. Mar. Biol. Annu. Rev. 30:273-335.

Pearson, T.H. 2001. Functional group ecology in soft-sediment marine benthos: The role of bioturbation. Oceanogr. Mar. Biol. Annu. Rev. 39:233-267.

Peddicord, R.K. and V.A. McFarland. 1978. Effects of suspended dredged material on aquatic animals. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Tech. Rep. D-78-29. 102 pp. + app.

Pineda, J. 2000. Linking larval settlement to larval transport: assumptions, potentials, and pitfalls. Oceanogr. East. Pacif. 1:84-105.

Poiner, I.R. and R. Kennedy. 1984. Complex pattern of change in the macrobenthos of a large sandbank following dredging. I. Community analysis. Mar. Biol. 78:335-352.

Posey, M. and T. Alphin. 2002. Resilience and stability in an offshore benthic community: Responses to sediment borrow activities and hurricane disturbance. J. Coast. Res. 18:685-697.

Pranovi, F., O. Giovanardi, and G. Franceschini. 1998. Recolonization dynamics in areas disturbed by bottom fishing gears. Hydrobiologia 375:125-135.

Pratt, S. 1973. Benthic fauna. In: Coastal and offshore environmental inventory, Cape Hatteras to Nantucket Shoals. University of Rhode Island, Marine Publication Series 2:5-1-5-70.

Probert, P.K. 1984. Disturbance, sediment stability, and trophic structure of soft-bottom communities. J. Mar. Res. 42:893-921.

Qian, P. 1999. Larval settlement of polychaetes. Hydrobiologia 402:239-253.

Reise, K. 2002. Sediment mediated species interactions in coastal waters. J. Sea Res. 48:127-141.

Research Planning, Inc., W.F. Baird & Associates Ltd., and Applied Marine Sciences, Inc. 2001. Development and design of biological and physical monitoring protocols to evaluate the long-term impacts of offshore dredging operations on the marine environment. U.S. Department of the Interior, Minerals Management Service, International Activities and Marine Minerals Division, Herndon, VA. OCS Report MMS 2001-089.

Resio, D.T. and B.A. Tracy. 1983. A Numerical Model for Wind-Wave Prediction in Deepwater. WIS Report 12, U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Wave Information Study, Vicksburg, MS.

Revsbech, N.P, B. Madsen, and B.B. Jorgensen. 1980. Oxygen in the sea bottom measured with a microelectrode. Science 207:1,355-1,356.

Rhoads, D.C., R.C. Aller, and M.B. Goldhaber. 1977. The influence of colonizing benthos on physical properties and chemical diagenesis on the estuarine seafloor, pp. 113-138. In: B.C. Coull (ed.) Ecology of Marine Benthos. University of South Carolina Press, Columbia, SC.

Rogers, C.S. 1990. Responses of coral reefs and reef organisms to sedimentation. Mar. Ecol. Prog. Ser. 62:185-202.

Ropes, J.W. 1978. Biology and distribution of surf clams (*Spisula solidissima*) and ocean quahogs (*Arctica islandica*) off the northeast coast of the United States. In: Proceedings of northeast clam industries: Management for the future. 27-28 April 1978, Hyannis, MA.

Ropes, J.W. 1980. Biological and fisheries data on the Atlantic surf clam, *Spisula solidissima* (Dillwyn). U.S. National Marine Fisheries Service, Northeast Fisheries Center. Sandy Hook Lab. Technical Series Report No. 24. 88 pp.

Rotunno, T. and R.K. Cowen. 1997. Temporal and spatial spawning patterns of the Atlantic butterfish, *Peprilus triacanthus*, in the South and Middle Atlantic Bights. Fish. Bull. 95(4):785-799.

Sackett, D.K., K.W. Able, and T.M. Grothues. 2007. Dynamics of summer flounder, *Paralichthys dentatus*, seasonal migrations based on ultrasonic telemetry. Est. Coast. Shelf. Sci. 74:119-130.

Sanders, H.L. 1968. Marine benthic diversity: A comparative study. Am. Nat. 102:243-282.

Sandifer, P.A. 1973. Distribution and abundance of decapod crustacean larvae in the York River estuary and adjacent lower Chesapeake Bay, Virginia, 1968-1969. Chesapeake Sci. 14:235-257.

SAS Institute, Inc. 2007. JMP Version 7.02. SAS Campus Drive, Building S, Cary, NC.

Scheltema, R.S. 1986. On dispersal and planktonic larvae of benthic invertebrates: an eclectic overview and summary of problems. Bull. Mar. Sci. 39:290-322.

Shanks, A.L. 1995. Mechanisms of cross-shelf dispersal of larval invertebrates and fish, pp. 323-367. In: L. McEdward (ed.), Ecology of Marine Invertebrate Larvae. CRC Press, Boca Raton, FL.

Sherk, J.A., Jr. 1971. The effects of suspended and deposited sediment on estuarine organisms: Literature summary and research needs. University of Maryland, Natural Resources Institute, Chesapeake Biological Laboratory Contribution Number 43. 73 pp.

Sherk, J.A., Jr. 1972. Current status of the knowledge of the biological effects of suspended and deposited sediments in Chesapeake Bay. Chesapeake Sci. 13(Suppl.):S137-S144.

Sherk, J.A., Jr. and L.E. Cronin. 1970. The effects of suspended and deposited sediments on estuarine organisms, an annotated bibliography of selected references. University of Maryland, Chesapeake Biological Laboratory, Natural Resources Institute, Reference Number 70-19. 62 pp.

Sherk, J.A., J.M. O'Connor, and D.A. Newman. 1975. Effects of suspended and deposited sediments on estuarine environments, pp. 541-558. In: L.F. Cronin (ed.), Estuarine Research Volume 2, Academic Press, New York, NY.

Sissenwine, M.P. 1984. Why do fish populations vary? pp. 59-94. In: R.M. May (ed.), Exploitation of Marine Communities. Springer-Verlag, Berlin.

Sisson, C.G. 2002. Dichotomous life history patterns for the nudibranch *Dendronotus frondosus* (Ascanius, 1774) in the Gulf of Maine. Veliger 45:290-298.

Slacum, H.W.,Jr., W.H. Burton, J.H. Vølstad, J. Dew, E. Weber, R. Llansó, and D. Wong. 2006. Comparisons between marine communities residing on sand shoals and uniform-bottom substrate in the Mid-Atlantic Bight. U.S. Department of the Interior, Minerals Management Service, International Activities and Marine Minerals Division, Herndon, VA. OCS Report MMS 2005-042. 149 pp. + apps.

Smith, C.R. and S.J. Brumsickle. 1989. The effects of patch size and substrate isolation on colonization modes and rates in an intertidal sediment. Limnol. Oceanogr. 34(7):1,263-1,277.

Smith, J.M., D.T. Resio, and A.K. Zundel. 1999. STWAVE: Steady-State Spectral Wave Model. Instructional Report CHL-99-1, U.S. Army Engineering Waterways Experiment Station, Vicksburg, MS.

Snedden, J.W. and R.W. Dalrymple. 1999. Modern shelf sand ridges: From historical perspective to a unified hydrodynamic and evolutionary mode, pp. 13–28. In: K.M. Bergman and J.W. Snedden (eds.), Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic Analysis and Sedimentologic Interpretation. Tulsa, Oklahoma: SEPM (Society for Sedimentary Geologists) Special Publication No. 64.

Snedden, J.W., R.D. Kreisa, R.W. Tillman, W.J. Schweller, S.J. Culver, and R.D. Winn. 1994. Stratigraphy and genesis of a modern shoreface-attached sand ridge, Peahala Ridge, New Jersey. J. Sed. Res. B64(4):560–581.

Snedden, J.H., R.P. Kreisa, R.K. Tillman, S.J. Culver, and W.J. Schweller. 1999. An expanded model for modern shelf sand ridge genesis and evolution on the New Jersey Atlantic shelf, pp. 147-164. In: K.M. Bergman and J.W. Snedden (eds.), Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic Analysis and Sedimentologic Interpretation. SEPM (Society for Sedimentary Geologists), Tulsa, OK. Special Publication No. 64.

Snelgrove, P.V.R. 1994. Hydrodynamic enhancement of invertebrate larval settlement in microdepositional environments: Colonization tray experiments in a muddy habitat. J. Exper. Mar. Biol. Ecol. 176:149-166.

Snelgrove, P.V.R. and C.A. Butman. 1994. Animal-sediment relationships revisited: Cause versus effect. Oceanogr. Mar. Biol. Annu. Rev. 32:111-177.

Snelgrove, P.V.R., J.P. Grassle, and C.A. Butman. 1998. Habitat selection by settling larvae of the surf clam, *Spisula solidissima* in flow and still water. J. Exper. Mar. Biol. Ecol. 231:171-190.

Snelgrove, P.V.R., J.P. Grassle, J.F. Grassle, R.F. Petrecca, and H. Ma. 1999. In situ habitat selection by settling larvae of marine soft-sediment invertebrates. Limnol. Oceanogr. 44:1,341-1,347.

Snelgrove, P.V.R., J.F. Grassle, J.P. Grassle, R.F. Petrecca, and K.I. Stocks. 2001. The role of colonization in establishing patterns of community composition and diversity in shallow-water sedimentary communities. J. Mar. Res. 59:813-831.

Sosnowski, R.A. 1984. Sediment resuspension due to dredging and storms: An analogous pair, pp. 609-618. In: R.L. Montgomery and J.W. Leach (eds.), Conference Proceedings, Dredging ’84, Dredging and Dredged Material Disposal. American Society of Civil Engineers, 14-16 November 1984, Clearwater Beach, FL.

Stehlik, L. 1993. Diet of the brachyuran crabs *Cancer irroratus, C. borealis*, and *Ovalipes ocellatus* in the New York Bight. J. Crust. Biol. 1,394:723-735.

Stehlik, L.L., R.A. Pikanowski, and D.G. McMillan. 2004. The Hudson-Raritan Estuary as a crossroads for distribution of blue (*Callinectes sapidus*), lady (*Ovalipes ocellatus*), and Atlantic rock (*Cancer irroratus*) crabs. Fish. Bull. 102:693-710.

Steimle, F.W. and C. Zetlin. 2000. Reef habitats in the Middle Atlantic Bight: Abundance, distribution, associated biological communities, and fishery resource use. Mar. Fish. Rev. 62(2):24-42.

Steiner, W.W., J.J. Luczkovich, and B.L. Olla. 1982. Activity, shelter usage, growth and recruitment of juvenile red hake, *Urophycis chuss*. Mar. Ecol. Prog. Ser. 7:125-135.

Stephenson, W.W.T., S.D. Cook, and J.S. Newland. 1978. The macrobenthos of the Middle Banks of Moreton Bay. Mem. Queensl. Mus. 18:95-118.

Stern, E.M. and W.B. Stickle. 1978. Effects of Turbidity and Suspended Material in Aquatic Environments: Literature Review. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Tech. Rep. D-78-21. 117 pp.

Steves, B.P., R.K. Cowen, and M.H. Malchoff. 1999. Settelment and nursery habitats for demersal fishes on the continental shelf of the New York Bight. Fish. Bull. 98:167-188.

Stocks, K.I. 2002. Flume experiments on post-settlement movement in polychaetes. J. Mar. Res. 60(5):743-762.

Stoner, A.W. 2003. What constitutes essential nursery habitat for a marine species? A case study of habitat form and function for the queen conch. Mar. Ecol. Prog. Ser. 257:275-289.

Strathmann, R.R., T.P. Hughes, A.M. Kuris, K.C. Lindeman, S.G. Morgan, J.M. Pandolfi, and R.R. Warner. 2002. Evolution of local-recruitment and its consequences for marine populations. Bull. Mar. Sci. Supp. (70):377-396.

Suess, E. 1980. Particulate organic flux in the oceans – surface productivity and oxygen utilization. Nature 288:260-263.

Sullivan, M.C., R.K. Cowen, K.W. Able, and M.P. Fahay. 2000. Spatial scaling of recruitment in four continental shelf fishes. Mar. Ecol. Prog. Ser. 207:141-154.

Sullivan, M.C., R.K. Cowen, K.W. Able, and M.P. Fahay. 2006. Applying the basin model: Assessing habitat suitability of young-of-the-year demersal fishes on the New York Bight continental shelf. Cont. Shelf. Res. 26:1,551-1,570.

Summerson, H.C. and C.H. Peterson. 1984. Role of predation in organizing benthic communities of a temperate-zone seagrass bed. Mar. Ecol. Prog. Ser. 15:63-77.

Swift, D.J.P and M.E. Field. 1981. Evolution of a classic sand ridge field: Maryland sector, North American inner shelf. Sedimentology 28:461-482.

Swift, D.J.P., J.W. Kofoed, F.P. Salsbury, and P. Sears. 1972. Holocene evolution of the shelf surface, central and southern Atlantic shelf of North America, pp. 499-575. In: D.J.P. Swift, D.B. Duane, and O.H. Pilkey (eds.), Shelf Sediment Transport: Process and Pattern. Dowden Hutchinson, and Ross, Stroudsburg, PA.

Tagatz, M.E. 1968. Biology of the blue crab, *Callinectes sapidus* Rathbun, in the St. Johns River, Florida. Fish. Bull. 67:17-33.

Tamburri, M.N., C.M. Finelli, D.S. Wethey, and R.K. Zimmer-Faust. 1996. Chemical induction of larval settlement behavior in flow. Biol. Bull. 191:367-373.

Taylor, A.S. 1990. The hopper dredge, pp. 59-63. In: D.D. Dickerson and D.A. Nelson (comps.), Proceedings of the National Workshop on Methods to Minimize Dredging Impacts on Sea Turtles, Jacksonville, FL, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Miscellaneous Paper EL-90-5.

Tenore, K.R. 1985. Seasonal changes in soft bottom macrofauna of the U.S. South Atlantic Bight, pp. 130-140. In: L.P. Atkinson, D.W. Menzel, and K.A. Bush (eds.), Oceanography of the Southeastern U.S. Continental Shelf. American Geophysical Union, Washington, DC.

Thistle, D. 1981. Natural physical disturbances and communities of marine soft bottoms. Mar. Ecol. Prog. Ser. 6:223-228.

Thompson, J.R. 1973. Ecological effects of offshore dredging and beach nourishment: A review. U.S. Army Engineer Waterways Experiment Station Miscellaneous Paper 1-73. U.S. Army Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, VA. Report 1-73.

Thompson, R.C., B.J. Wilson, M.L. Tobin, A.S. Hill, and S.J. Hawkins. 1996. Biologically generated habitat provision and diversity of rocky shore organisms at a hierarchy of spatial scales. J. Exper. Mar. Biol. Ecol. 202:73-84.

Thorson, G. 1957. Bottom communities (sublittoral or shallow shelf). In: J.W. Hedgpeth (ed.), Treatise on Marine Ecology and Palaeoecology, Volume I. Mem. Geol. Soc. Am. 67:461-534.

Thorson, G. 1966. Some factors influencing the recruitment and establishment of marine benthic communities. Netherlands. J. Sea Res. 3(2):267-293.

Thrush, S.F., R.B. Whitlatch, R.D. Pridmore, J.E. Hewitt, V.J. Cummings, and M.R. Wilkinson. 1996. Scale-dependent recolonization: The role of sediment stability in a dynamic sandflat habitat. Ecology 77:2,472-2,487.

Thrush, S.F., J.E. Hewitt, V.J. Cummings, M.O. Green, G.A. Funnell, and M.R. Wilkinson. 2000. The generality of field experiments: Interactions between local and broad-scale processes. Ecology 81:399-415.

Thrush, S.F., J.E. Hewitt, G.A. Funnell, V.J. Cummings, J. Ellis, D. Schultz, D.Talley, and A. Norkko. 2001. Fishing disturbance and marine biodiversity: the role of habitat structure in simple soft-sediment systems. Mar. Ecol. Prog. Ser. 223:277-286.

Thrush, S.F., J.E. Hewitt, P.M. Herman, and T. Ysebaert. 2005. Multi-scale analysis of species-environment relationships. Mar. Ecol. Prog. Ser. 302:13-26.

Todd, C.D. 1998. Larval supply and recruitment of benthic invertebrates: do larvae always disperse as much as we believe? Hydrobiologia 375:1-21.

Tolley, S.G. and A.K. Volety. 2005. The role of oysters in habitat use of oyster reefs by resident fishes and decapod crustaceans. J. Shellfish Res. 24:1,007-1,012.

Tracy, B.A. and A. Cialone. 2004. Comparison of Gulf of Mexico Wave Information Studies (WIS) 2-G Hindcast with 3-G Hindcasting. Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Waterways Experiment Station, Vicksburg, Mississippi, USA.

Trowbridge, J. H. 1995. A mechanism for the formation and maintenance of shore-oblique sand ridges on storm-dominated shelves. J. Geophys. Res. 100(C8):16,071-16,086.

Turbeville, D.B. and G.A. Marsh. 1982. Benthic fauna of an offshore borrow area in Broward County, Florida. U.S. Army Corps of Engineers, Coastal Engineering Research Center, Miscellaneous Report 82-1. 43 pp.

U.S. Army Corps of Engineers (USACE). 1989. Atlantic Coast of Maryland Hurricane Protection Project: Renourishment borrow study. U.S. Army Corps of Engineers, Baltimore District, Baltimore, MD.

U.S. Army Corps of Engineers (USACE). 2008. Atlantic Coast of Maryland Shoreline Protection Project Final Supplemental Environmental Impact Statement General Reevaluation Study: Borrow Sites for 2010 – 2044. U.S. Army Corps of Engineers, Baltimore District, Baltimore, MD. 125 pp. + apps.

Ullberg, J. and E. Ólafsson. 2004. Free-living marine nematodes actively choose habitat when descending from the water column. Mar. Ecol. Prog. Ser. 260:141-149.

van Dalfsen, J.A., K. Essink, H. Toxvig Madsen, J. Birklund, J. Romero and M. Manzanera. 2000. Differential response of macrozoobenthos to marine sand extraction in the North Sea and the Western Mediterranean. ICES J. Mar. Sci. 57:1,439-1,445.

Van Dolah, R.F., D.R. Calder, and D.M. Knott. 1984. Effects of dredging and open-water disposal on benthic macroinvertebrates in a South Carolina estuary. Estuaries 7:28-37.

Van Dolah, R.F., B.J. Digre, P.T. Gayes, P. Donovan-Ealy, and M.W. Dowd. 1998. An evaluation of physical recovery rates in sand borrow sites used for beach nourishment projects in South Carolina. South Carolina Department of Natural Resources, Marine Resources Research Institute for the U.S. Department of the Interior, Minerals Management Service, Office of International Activities and Marine Minerals. 76 pp. + app.

Van Hoey, G., K. Guilini, M. Rabaut, M. Vinex, and S. Degraer. 2008. Ecological implications of the presence of the tube-building polychaete *Lanice conchilega* on soft-bottom benthic ecosystems. Mar. Biol. 154:1,009-1,019.

Vasslides, J.M. and K.W. Able. 2008. Importance of shoreface sand ridges as habitat for fishes off the northeastern coast of the United States. Fish. Bull. 106:93-107.

Veer, H.W. van der, J.N. Bergman, and J.J. Beukema. 1985. Dredging activities in the Dutch Wadden Sea: Effects on macrobenthic infauna. Neth. J. Sea Res. 19:183-190.

Virginia Institute of Marine Science (VIMS). 2000. Environmental Survey of Potential Sand Resource Sites Offshore Delaware and Maryland. Final Report to the U.S. Department of the Interior, Minerals Management Service, International Activities and Marine Minerals Division, Herndon, VA. OCS Study MMS 2000-055.

Viscido, S.V., D.E. Stearns, and K.W. Able. 1997. Seasonal and spatial patterns of an epibenthic crustacean assemblage in northwest Atlantic Continental Shelf waters. Estuar. Coast. Shelf Sci. 45:377-392.

Voultsiadou, E., M. Pyrounaki, and C. Chintiroglou. 2007. The habitat engineering tunicate *Microcosmus sabatieri* Roule, 1885 and its associated peracarid epifauna. Estuar. Coast. Shelf Sci. 74:197-204.

Walker, T.A. and G. O'Donnell. 1981. Observations on nitrate, phosphate and silicate in Cleveland Bay, Northern Queensland. Aust. J. Mar. Fresh. Res. 32:877-887.

Wang, F. and P.M. Chapman. 1998. Biological implications of sulfide in sediment-a review focusing on sediment toxicity. Environ. Toxicol. Chem. 18:2,526-2,532.

Wehrtmann, I.S. 1994. Larval production of the caridean shrimp, *Crangon septemspinosa*, in waters adjacent to Chesapeake Bay in relation to oceanographic conditions. Estuaries 17:509-518.

Weissburg, M.J., M.C. Ferner, D.P. Pisut, and D.L. Smee. 2002. Ecological consequences of chemically mediated prey perception. J. Chem. Ecol. 28(10):1,953-1,970.

West, H., J. Harrigan, and S. Pierce. 1984. Hybridization of two populations of a marine opisthobranch with different developmental patterns. Veliger 26:199-206.

Weston, D.P. 1988. Macrobenthos-sediment relationships on the continental shelf off Cape Hatteras, North Carolina. Cont. Shelf Res. 8:267-286.

Whitlatch, R.B. 1977. Seasonal changes in the benthic fauna inhabiting the intertidal sand and mud flats of Barnstable Harbor, MA. Biol. Bull. 152:275-294.

Whitlatch, R.B., A.M. Lohrer, S.F. Thrush, R.D. Pridmore, J.E. Hewitt, V.J. Cummings, and R.N. Zajac. 1998. Scale-dependent benthic recolonization dynamics: Life stage-based dispersal and demographic consequences. Hydrobiologia 375:217-226.

Wigley, R.L. and R.B. Theroux. 1981. Atlantic continental shelf and slope of the United States-macrobenthic invertebrate fauna of the Middle Atlantic Bight region-faunal composition and quantitative distribution. U.S. Geological Survey Professional Paper 529-N. 198 pp.

Wilber, D.H. and D.G. Clarke. 2001. Biological effects of suspended sediments: A review of suspended sediment impacts on fish and shellfish with relation to dredging activities in estuaries. N. Am. J. Fish. Mgmt. 21:855-875.

Wilbur, P. and M. Stern. 1992. A re-examination of infaunal studies that accompany beach nourishment projects, pp. 242-257. In: New Directions in Beach Management: Proceedings of the 5th Annual National Conference on Beach Preservation Technology, Florida Shore and Beach Preservation Association, Tallahassee, FL.

Wilcox, J.R. and H.P. Jeffries. 1974. Feeding habits of the sand shrimp *Crangon septemspinosa*. Biol. Bull. 146:424-434.

Wilk, S.J., W.W. Morse, and L.L. Stehlik. 1990. Annual cycles of gonad-somatic indices as indicators of spawning activity for selected species of finfish collected from the New York Bight. Fish. Bull. 88:775-786.

Winget, R.R., D. Maurer, and H. Seymour. 1974. Occurrence, size composition and sex ratio of the rock crab, *Cancer irroratus* Say and the spider crab, *Libinia emarginata* Leach in Delaware Bay. J. Nat. Hist. 8:199-205.

Witman, J. D., M.R. Patterson, and S.J. Genovese. 2004. Benthic-pelagic linkages in subtidal communities: influence of food subsidy by internal waves, pp. 133-153. In: G.A. Polis, M.E. Power, and G.R. Huxel, Food Webs at the Landscape Level. University of Chicago Press. 548 pp.

Witting, D.A. and K.W. Able. 1993. Effects of body size on probability of predation for juvenile summer and winter flounder based on laboratory experiments. Fish. Bull. 91:577-581.

Witting, D.A. and K.W. Able. 1995. Predation by sevenspine bay shrimp, *Crangon septemspinosa*, on winter flounder, *Pleuronectes americanus*, during settlement: laboratory observations. Mar. Ecol. Prog. Ser. 123:23-31.

Woodin, S.A. 1981. Disturbance and community structure in a shallow water sand flat. Ecology 62:1,052-1,066.

Woodin, S.A., S.M. Lindsay, and D.S. Wethey. 1995. Process-Specific Recruitment Cues in Marine Sedimentary Systems. Biol. Bull. 189:49-58.

Wright, D.G. 1977. Artificial islands in the Beaufort Sea: A review of potential impacts. Department of Fisheries and Environment, Winnipeg, Manitoba. 38 pp.

Wu, R.S.S. and P.K.S. Shin. 1997. Sediment characteristics and colonization of soft-bottom benthos: A field manipulation experiment. Mar. Biol. 128:475-487.

Zajac, R.N., R.B. Whitlatch, and S.F. Thrush. 1998. Recolonization and succession in soft-sediment infaunal communities: The spatial scale of controlling factors. Hydrobiologia 375:227-240.

Zajac, R.N., R.S. Lewis, L.J. Poppe, D.C. Twichell, J. Vozarik, and M.L. DiGiacomo-Cohen. 2003. Responses of infaunal populations to benthoscape structure and the potential importance of transition zones. Limnol. Oceanogr. 48:829-842.

Zeng, C. and E. Naylor. 1996. Endogenous tidal rhythms of vertical migration in field collected Zoea-1 larvae of the shore crab *Carcinus maenas*: Implications for ebb tide offshore dispersal. Mar. Ecol. Prog. Ser. 132:71-82.