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FINAL REPORT

COLLECTION OF ENVIRONMENTAL DATA WITHIN SAND RESOURCE AREAS OFFSHORE NORTH CAROLINA AND THE ENVIRONMENTAL IMPLICATIONS OF SAND REMOVAL FOR COASTAL AND BEACH RESTORATION

Volume I: Main Text

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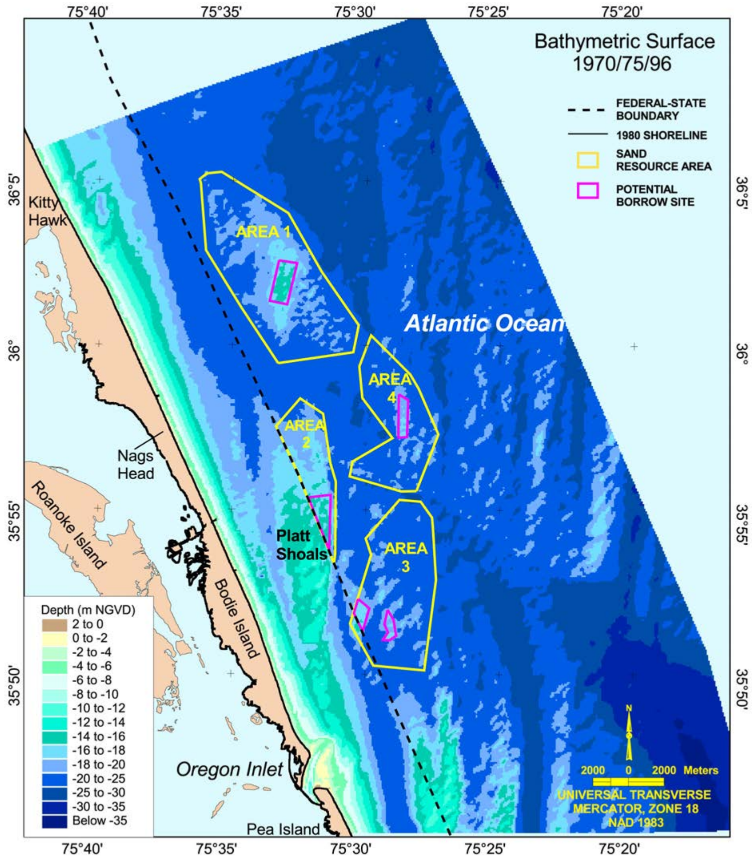

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COLLECTION OF ENVIRONMENTAL DATA WITHIN SAND RESOURCE AREAS OFFSHORE NORTH CAROLINA AND THE ENVIRONMENTAL IMPLICATIONS OF SAND REMOVAL FOR COASTAL AND BEACH RESTORATION

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Dr. Mark R. Byrnes of Applied Coastal Research and Engineering, Inc. (Applied Coastal) served as Project Manager; Physical Processes Component Manager; authored Sections 1.0 (Introduction), 2.1 (Offshore Sedimentary Environment), 3.0 (Regional Geomorphic Change), 7.1 (Offshore Sand Resource Areas), and 7.4.1 (Historical Sediment Transport Patterns); co-authored with Dr. Richard M. Hammer Sections 7.7 (Potential Cumulative Effects) and 8.0 (Conclusions); and was Co-Editor of the report. Dr. Richard M. Hammer of Continental Shelf Associates, Inc. (CSA) served as the Biological Component Manager; authored Sections 7.5.1 (Effects of Offshore Dredging on Benthic Fauna) and 7.5.2 (Recolonization Rate and Success); and was Co-Editor of the report.

Other Applied Coastal personnel who participated in the project included Mr. Sean W. Kelley and Mr. John S. Ramsey who co-authored Sections 2.2.4 (Waves and Wave-Generated Currents), 2.2.5 (Nearshore Sediment Transport), 4.0 (Assessment of Wave Climate Impact by Offshore Borrow Sites), 5.2 (Offshore Sediment Transport), 7.2 (Wave Transformation Modeling, 7.4.2 (Sediment Transport Modeling at Potential Borrow Sites), and 7.4.3 (Nearshore Sediment Transport Potential). Ms. Jessica M. Côté and Mr. Jon D. Wood co-authored Sections 2.2.1 (Tidal Currents), 2.2.2 (Wind-Generated Currents), 2.2.3 (Density-Driven Currents), 5.1 (Currents and Circulation), 5.1.2 (Summary of Flow Regimes at Offshore Borrow Sites), and 7.3 (Currents and Circulation). Ms. Jessica L. Baker and Ms. Feng Li were responsible for shoreline and bathymetric change data compilation and surface modeling. Ms. Shelley Johnston assisted with report preparation related to background literature on the offshore sedimentary environment. Ms. Elizabeth Hunt was responsible for report compilation and editorial assistance during production of the report.

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LIST OF ABBREVIATIONS

μ	Micron
ADCP	Acoustic Doppler Current Profiler
ASTM	American Society for Testing Materials
BVA	Barry Vittor & Associates, Inc.
CEQ	Council on Environmental Quality
CERC	Coastal Engineering Research Center
CETAP	Cetacean and Turtle Assessment Program
cm	centimeter
CSA	Continental Shelf Associates, Inc.
deg	degrees
DGPS	Differential Global Positioning System
EA	Environmental Assessment
EEZ	Exclusive Economic Zone
EFH	Essential Fish Habitat
EIS	Environmental Impact Statement
FMP	Fishery Management Plan
FRF	Field Research Facility
ft	feet
g	gram
HAPC	Habitat Areas of Particular Concern
HMS	Highly Migratory Species
Hz	Hertz
kg	kilogram
km	kilometers
l	liter
LPIL	Lowest Practical Identification Level
m	meter
MAB	Mid-Atlantic Bight
MAB-NURC	Mid-Atlantic Bight National Undersea Research Center
MAFMC	Mid-Atlantic Fisheries Management Council
MARMAP	Marine Monitoring, Assessment, and Prediction Program
MCM	million cubic meters
MCY	million cubic yards
mg/l	milligrams per liter
MLLW	Mean Lower Low Water
MLW	Mean Low Water
mm	Millimeter
MMB	Marsh-McBirney current meter
MMS	Minerals Management Service
MSL	Mean Sea Level
MT	metric tons
MWL	Mean Water Level
NAD	North American Datum
NCGS	North Carolina Geological Survey
NEFMC	New England Fisheries Management Council
NEPA	National Environmental Policy Act
NGDC	National Geophysical Data Center
NGVD	National Geodetic Vertical Datum
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
OCS	Outer Continental Shelf

LIST OF ABBREVIATIONS (CONTINUED)

OCSLA	Outer Continental Shelf Lands Act
OSI	Organism Sediment Index
Ppt	parts per thousand
RAC	Roanoke-Albermarle Channel
REF/DIF S	Refraction/Diffraction Model for Spectral Wave Conditions
RPD	Redox Potential Discontinuity
SAFMC	South Atlantic Fishery Management Council
sec	seconds
SMS	Shoreline Modeling System
SOD	Sediment Oxygen Demand
SPI	Sediment Profile Image
STWAVE	Steady-State Spectral Wave Model
USACE	U.S. Army Corps of Engineers
USC & GS	U.S. Coast and Geodetic Survey
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
WES	Waterways Experiment Station
WIS	Wave Information Study
yd	yard
yr	year

1.0 INTRODUCTION

The Minerals Management Service (MMS), a bureau within the U.S. Department of the Interior, has responsibility for managing all mineral resources on the Federal Outer Continental Shelf (OCS), a zone that extends from three miles seaward of State coastline boundaries to 200 miles offshore. Although most interest in this zone relates to oil and gas resources, the potential for exploitation of sand resources as a source for beach and barrier islands restoration has grown rapidly in the last several years as similar resources in State waters are being depleted or polluted. Extraction of sand resources in Federal waters may be preferred relative to State waters due to concerns over changes in physical and biological oceanographic conditions resulting from large quantities of material dredged from resource areas impacted by waves and currents. This has generated a need for technical information to ensure that offshore minerals are developed with due concern for potential environmental considerations.

Houston (1995, 2002) discusses the value of beaches and their maintenance through beach nourishment to America's economy. Not only are beaches the dominant component of most coastal economies, but they also provide a certain level of protection against high winds and waves associated with storms. Although the earliest seaside resort along the Outer Banks (Nags Head) developed in the 1830s and was flourishing by the beginning of the Civil War (Dolan and Lins, 1986; Pilkey et al., 1998), it only has been since the 1940s that coastal development has grown steadily along the Outer Banks with the construction of bridges from the mainland and roads on the barrier islands. Miller (1993) stresses the importance of coastal and marine tourism as the world's largest industry and its continual rise over the past 50 years. As such, beaches are key elements of coastal tourism because they represent the leading tourist destination.

Coastal community master plans are being developed and revised to address concerns associated with population growth, storm protection, recreation, waste disposal and facilities management, and zoning (Williams, 1992). Often, problems stemming from these issues are in direct conflict with natural coastal processes. Some of the more direct problems are related to coastal erosion and storm protection. The practice of replenishing beaches with sand from upland and nearshore sources as protection for community infrastructure has increased in direct relation to population growth. As coastal and nearshore borrow areas become depleted, and our knowledge of environmental effects of coastal sand mining develop, alternate sources of aggregate and beach fill must be evaluated for offshore sites to meet specific societal needs. In many cases, sand resource extraction from the OCS may prove environmentally preferable to nearshore borrow areas due to potential changes in waves and currents as large quantities of sand are dredged from the seafloor.

The MMS has significant responsibilities with respect to potential environmental impacts of sand and gravel mining. Existing regulations governing sand and gravel mining provide a framework for comprehensive environmental protection during operations. Specific requirements exist for evaluations and lease stipulations that include appropriate mitigation measures (Hammer et al., 1993; Woodworth-Lynas and Davis, 1996). Guidelines for protecting the environment stem from a wide variety of laws, including the OCS Lands Act (OCSLA), National Environmental Policy Act (NEPA), Endangered Species Act, Marine Mammals Protection Act, and others. Regulations require activities to be conducted in a manner that prevents or minimizes the likelihood of any occurrences that may cause damage to the environment. The MMS takes a case-by-case approach in conducting environmental analyses, as required by NEPA and the Council on Environmental Quality (CEQ) regulations.

1.1 STUDY AREA AND BORROW SITE CHARACTERISTICS

The inshore portion of the continental shelf, seaward of the Federal-State OCS boundary and within the North Carolina Exclusive Economic Zone (EEZ), encompasses the project study area (Figure 1-1). Four potential sand resource areas were identified offshore Dare County, NC in Federal waters by the North Carolina Geological Survey (NCGS). The seaward limit of the study area is generally within about 15 km of the shoreline. Sand resource areas are located on the North Carolina OCS between the 10- and 20-m depth contours. The continental shelf surface within the study area contains many sand ridges formed during the Holocene transgression (Boss et al., 2002; see Section 2.0). Sand ridges 2- to 5-m high and 0.5- to 1.5-km apart represent the primary sand resource targets of this study. For sand resource areas on the northern North Carolina continental shelf, average shoal relief is about 2 to 3 m.

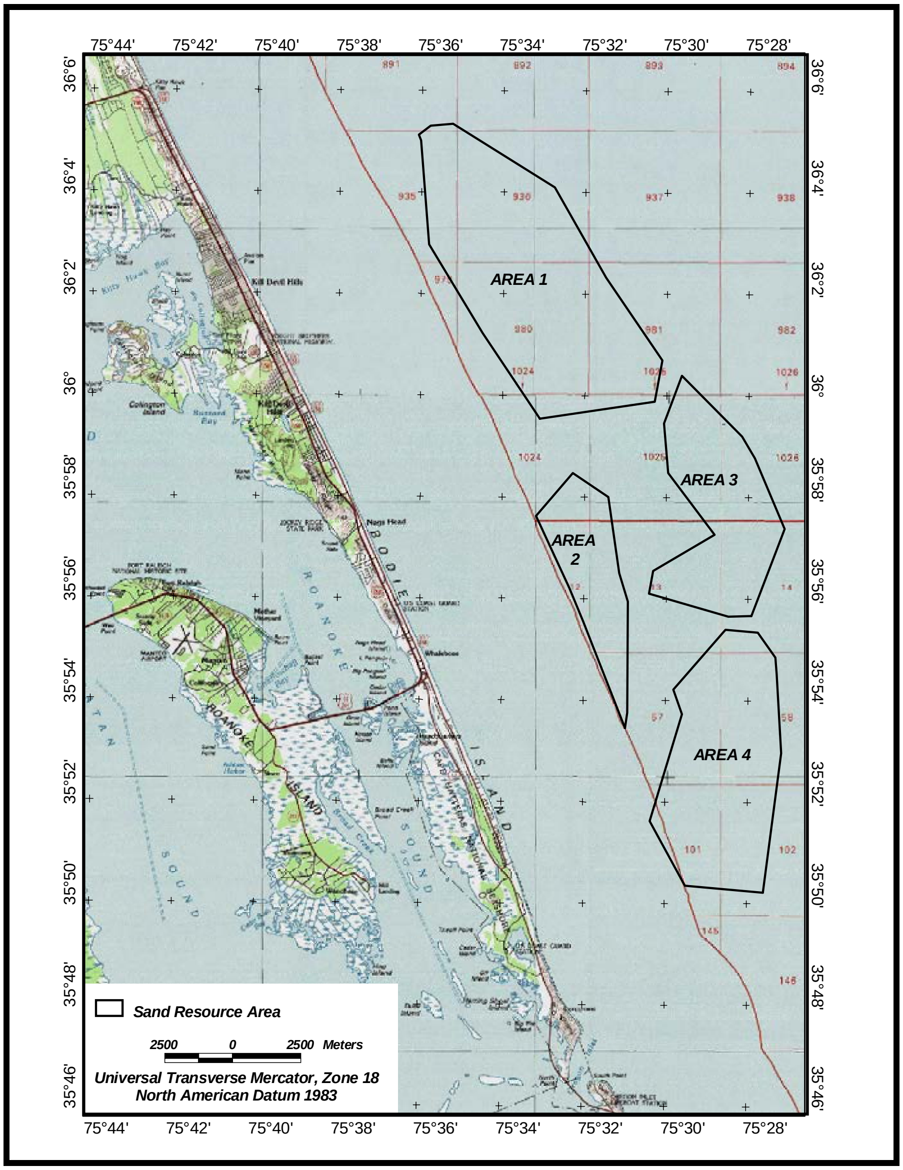

Figure 1-1. Location diagram illustrating sand resource areas and Federal-State boundary offshore Dare County, NC.

Sand Resource Areas 1, 2, 3, and 4 contain borrow sites with the greatest potential for future use. Each area has specific geologic and geographic characteristics that make it viable as a sand resource for specific segments of coast. All sand resource areas are very similar geologically (medium sand size ridge deposits with relief of 2 m or greater and resource volumes of at least 1 million cubic meters [MCM]). However, sand from the eastern borrow site in Area 3 has a median grain size of 0.21 mm (fine sand), the smallest grain size for any of the potential resource areas. Regardless, all identified potential sand borrow sites are of great interest to the State, primarily due to their proximity to eroding beaches critical for storm protection and recreation. Physical processes (waves and currents) and biological habitat at borrow sites on the sand ridges illustrate relatively minor variability offshore North Carolina. However, habitat variability within resource areas varies widely depending on surface area boundaries and geographic position. Although these four potential sand resource areas were designated as ones with greatest potential, it is possible that sand could be dredged from intervening offshore areas.

The amount of dredging that occurs at any site is a function of Federal, State, and local needs for beach replenishment. There is no way of predicting the exact sand quantities needed in the foreseeable future, so a representative value for any given project was estimated based on discussions with State personnel and the MMS. Preliminary analysis of short-term impacts (storm and normal conditions) at specific sites along the coast landward of sand borrow sites indicates that about 1 MCM of sand could be needed for a given beach replenishment event. Long-term shoreline change data sets suggest that a replenishment interval of about 5 to 10 years would be expected to maintain beaches. This does not consider the potential for multiple storm events impacting the coast over a short time interval, nor does it consider longer time intervals absent of destructive storm events. Instead, the estimate represents average change over decades that is a reasonable measure for coastal management applications.

Given the quantity of 1 MCM of sand per beach replenishment event, the surface area covered for evaluating potential environmental impacts is a function of average dredging depth. Two factors should be considered when establishing dredging practice and depth limits for proposed extraction scenarios. First, regional shelf sediment transport patterns should be evaluated to determine net transport directions and rates. It is more effective to dredge the leading edge of a migrating shoal, and infilling of dredged areas occurs more rapidly at these sites (Byrnes and Groat, 1991; Van Dolah et al., 1998). Second, shoal relief above the ambient shelf surface should be a determining factor controlling depth of dredging. Geologically, shoals form and migrate on top of the ambient shelf surface, indicating a link between fluid dynamics, sedimentology, and environmental evolution (Swift et al., 1976). As such, average shoal relief is a reasonable depth threshold for maintaining environmentally-consistent sand extraction procedures.

For sand resource areas within the study area, maximum shoal relief is on the order of 5 m, and average shoal relief is about 2 to 3 m. Although modern beach replenishment practice varies depending on geographic location and level of funding for the North Carolina coast, it is reasonable to expect multiple replenishment events over the next 50 years from the designated sand resource areas. As such, one shoal deposit was selected from each resource area based on geological characteristics. A maximum excavation depth was determined for each specific site. In Area 1, a 2.40×10^6 m^2 borrow site was defined based on shoal morphology (Figure 1-2). Bathymetry data and geological samples indicate a maximum excavation depth of 3 m (Boss and Hoffman, 2001), resulting in a 7.2 MCM extraction scenario; median grain diameter for the deposit is 0.41 mm (Table 1-1). The same procedure was used for selected

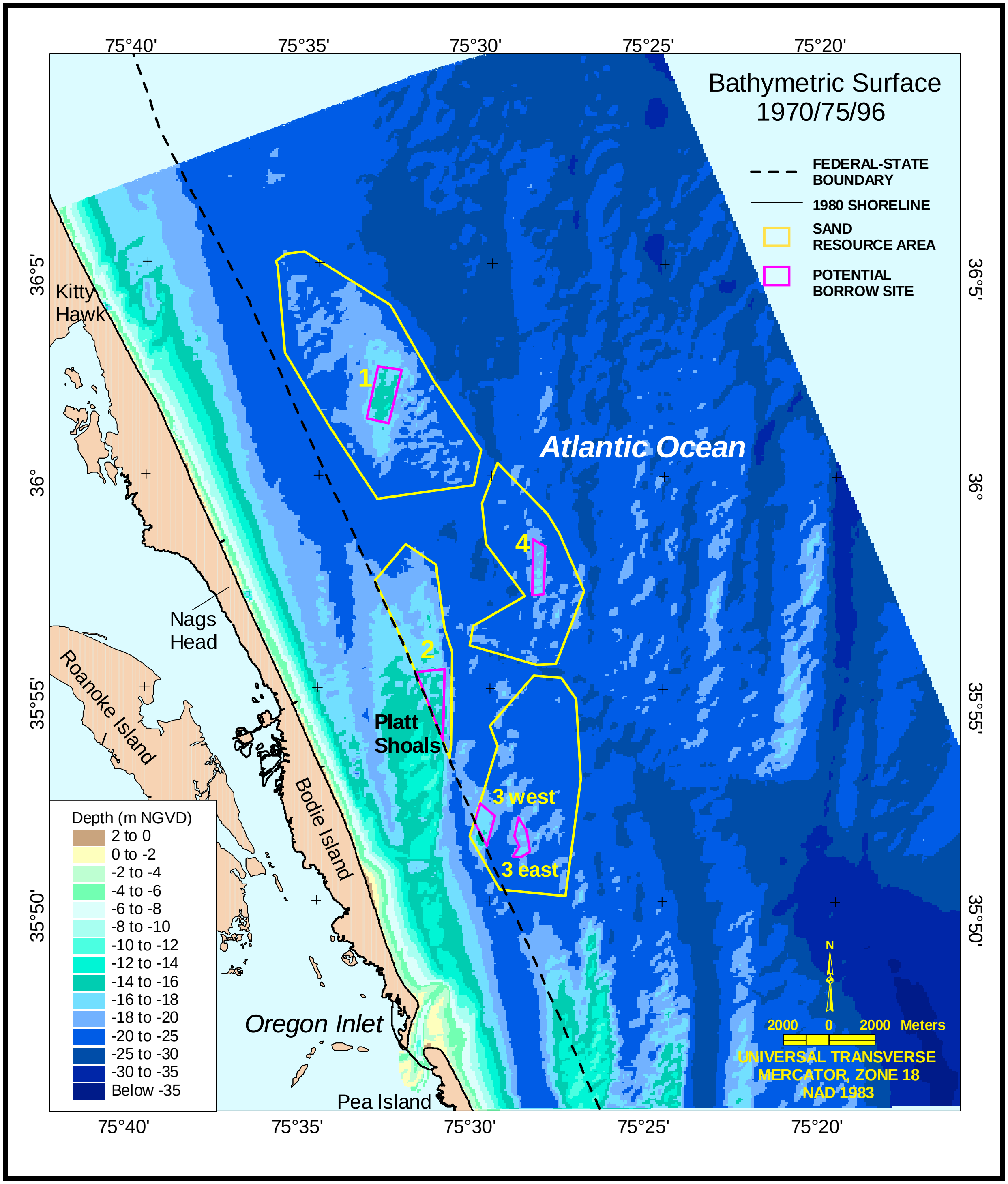

Figure 1-2. Location diagram illustrating potential sand borrow sites relative to shelf morphology offshore Dare County, NC.

borrow sites at the other three sand resource areas. The selected borrow site in Area 2 encompassed 1.95 x 10^6 m^2 of seafloor to a depth of 3 m, resulting in 5.8 MCM of sand. Borrow site 3 west in Area 3 covers 0.83 x 10^6 m^2 of seafloor to a maximum excavation depth of 3 m. The borrow site contains 2.5 MCM of sand. For borrow site 3 east, surface area encompassed

0.70×10^6 m^2. The maximum excavation depth was 2 m, resulting in 1.4 MCM of sand. The potential sand borrow site in Area 4 covers approximately 1.16×10^6 m^2 of seafloor. For a 2-m excavation depth, the resulting sand volume is 2.3 MCM. The sand volume at each of these borrow sites is at least equal to the quantity of sand needed for any single expected replenishment event, so all analyses were used to estimate potential cumulative effects of multiple extraction scenarios.

Table 1-1. Sand Resource Characteristics at Potential Borrow Sites in Resource Areas Offshore North Carolina.

Borrow Site	Sand Volume (MCM)	Excavation Depth (m)	D10 (mm)	D50 (mm)	D90 (mm)	% Sand and Gravel
1	7.2	3	0.85	0.41	0.26	99.7
2	5.8	3	1.60	0.50	0.21	99.8
3 east	1.4	2	0.42	0.21	0.13	99.7
3 west	2.5	3	0.45	0.27	0.14	99.9
4	2.3	2	0.83	0.36	0.19	100.0

D10 = grain diameter above which 10% of the distribution is retained; D50 = median grain diameter; D90 = grain diameter above which 90% of the distribution is retained

1.2 STUDY PURPOSE

The primary purpose of this study was to address environmental concerns associated with the potential for dredging sand from the OCS offshore Dare County, NC for beach replenishment and to document the findings in a technical report. The primary environmental concerns focused on biological and physical components of the environment. To this end, seven study objectives were identified:

- Compile and analyze existing oceanographic literature and data sets to develop an understanding of environmental conditions offshore North Carolina and the ramifications of dredging operations at selected sand borrow sites;
- Use physical processes data sets and wave climate simulations to predict wave transformation under natural conditions and in the presence of proposed dredging activities;
- Determine existing coastal and nearshore sediment transport patterns using historical data sets, and predict future changes resulting from proposed sand dredging operations;
- Design and conduct field data collection efforts for biological characterization to supplement existing information;
- Analyze field data for biological characterization and address basic environmental concerns regarding potential sand dredging operations;
- Evaluate the potential environmental effects of multiple dredging scenarios; and
- Develop a document summarizing the information generated to assist with decisions concerning preparation of Environmental Assessments and Environmental Impact Statements to support negotiated agreements.

In meeting these objectives, this document should provide invaluable information regarding environmental concerns examined relative to proposed future sand dredging in support of beach replenishment needs from offshore North Carolina.

1.3 STUDY APPROACH

Physical and biological processes data were analyzed to assess the potential impacts of offshore dredging activities within the study area to minimize or preclude long-term adverse environmental impacts at potential borrow sites and along the coastline landward of resource areas. In addition, wave transformation and sediment transport numerical modeling were employed to simulate the physical environmental effects of proposed sand dredging operations to ensure that offshore sand resources are developed in an environmentally sound manner.

Five primary study elements were specified by the MMS in Task 1 (Data Collection and Analysis) of the Request for Proposal for addressing environmental concerns associated with offshore sand dredging for beach replenishment. They included:

- Characterize benthic ecological conditions, using existing data sets and data collected from field work, in and around the proposed sand borrow areas;
- Evaluate the benthic infauna present in the proposed borrow areas, and assess the potential effects of offshore sand dredging on these organisms, including an analysis of the potential rate and success of recolonization following dredging;
- Develop a schedule of best and worst times for offshore sand dredging in relation to transitory pelagic species;
- Evaluate the potential modifications to waves that propagate within the study area due to offshore sand dredging within the proposed sand resource areas; and
- Evaluate the impact of offshore dredging and consequent beach replenishment in terms of potential alteration to sediment transport patterns, sedimentary environments, and impacts to local shoreline processes.

The first three study elements focus primarily on biology and associated ecological impacts relative to potential sand dredging operations. The final two elements concentrate on potential alterations to physical processes and sedimentary environments, as well as potential shoreline response to incident waves and currents resulting from dredging operations. The scientific approach used to address each of the study elements is presented below. The remaining study tasks (2-14) focused on document preparation and project management requirements.

1.3.1 Ecological Conditions

The goal of this study element was to characterize benthic ecological conditions in and around the four sand resource areas. This phase of the study primarily focused on field data collection efforts conducted in May and September 1998 (presented in detail in Section 6.0). Existing literature and data were compiled and summarized to characterize the ecological environment and to form the foundation upon which field surveys were designed. Biological field surveys were conducted to characterize infauna, epifauna, demersal fishes, sediment grain size, and water column parameters.

1.3.2 Benthic Infaunal Evaluation

The goal of this study element was to assess the potential effects of offshore dredging on benthic infauna and analyze the potential rate and success of recolonization following cessation of dredging activities. Existing literature and data on dredging effects were searched and synthesized then combined with results from the biological field surveys to examine potential benthic effects and recolonization in the sand resource areas. Because monitoring surveys of actual sand mining operations were not to be conducted, the assessment of potential effects and recolonization was based only on field survey characterizations and existing literature.

1.3.3 Project Scheduling

The goal of this study element was to determine the best and worst times for offshore dredging relative to pelagic species. Environmental windows are temporal constraints placed on dredging activities to protect biological resources from potentially detrimental effects (Dickerson et al., 1998). Existing information was collected and summarized concerning the seasonal occurrence of pelagic species and potential impacts from dredging. Project scheduling considerations for pelagic species then were analyzed based on this information.

1.3.4 Wave Modifications

The goal of this study element was to perform wave transformation numerical modeling to predict the potential for adverse modification of waves resulting from sand dredging operations. Changes in bathymetry in sand resource areas can cause wave energy focusing resulting in substantial alterations in sediment transport at the site of dredging operations, as well as along the shoreline landward of the borrow site. Because the purpose of dredging offshore sand from a specific site will be driven by the need for beach replenishment, it is critical to understand the impact of changing wave transformation patterns on shoreline response before potentially exacerbating a problem. Numerical comparisons of existing and post-dredging impacts provided a means of documenting modifications to waves as they crossed the four sand resource areas (detailed in Section 4.0).

1.3.5 Sediment Transport Patterns

The goal of this study element was to predict changes in sediment transport patterns resulting from potential sand dredging operations using numerical information generated from wave transformation modeling, combined with existing offshore current data. Sediment transport rates were quantified for sand resource areas using an analytical approach, whereas transport rates at the shoreline were determined numerically using output from wave transformation numerical modeling (detailed in Section 5.0).

Historical shoreline and bathymetry data were compiled to document regional sediment transport patterns over a 100+ year time period. Net changes in sediment erosion and deposition on the shelf surface offshore North Carolina provided a direct method for identifying patterns of sediment transport and quantifying net rates of change throughout potential sand resource areas (detailed in Section 3.0). These data also were used to calibrate numerical results for direction and magnitude of sediment transport.

1.4 DOCUMENT ORGANIZATION

This document was organized into nine major sections as follows:

- Introduction
- Environmental Setting
- Regional Geomorphic Change
- Wave Transformation Numerical Modeling and Nearshore Sediment Transport
- Circulation and Offshore Sediment Transport Dynamics
- Biological Field Surveys
- Potential Effects
- Conclusions
- Literature Cited

The sections are presented in a different order than the list of study elements in the RFP. Because benthic and pelagic biological characteristics are in part determined by spatially varying physical processes throughout the study area, physical processes analyses are summarized first.

In addition to the main document, appendices were prepared in support of many of the analyses presented in each section of the report. Furthermore, an Executive Summary, a Technical Summary, and a Non-Technical Summary will be prepared as separate documents to provide a brief description of the study for audiences ranging from researchers to non-technical people.

2.0 ENVIRONMENTAL SETTING

The east coast of the U.S. is a trailing edge coast with gentle slopes and a broad continental shelf. The Outer Banks of North Carolina are barrier islands that front Pamlico, Albemarle, and Currituck Sounds (Figure 2-1) and protect the mainland of North Carolina south of Cape Lookout from Atlantic Ocean waves and currents. The North Carolina barrier island chain is 320 km long and consists of multiple barrier islands separated by 22 inlets (Figure 2-2). The present location of the barriers was established about 4,000 years ago when the rate of Holocene sea level rise decreased (Swift et al., 1972). The project area encompasses about 40 km of Atlantic Ocean coast from Oregon Inlet (35°47'N) north to Kitty Hawk (36°05'N). Although the offshore Federal-State boundary marks the direct landward limit of the study area (Figure 1-1), the ultimate use of sand extracted from the OCS is for beach replenishment along Bodie Island beaches in Dare County (Figure 2-3). Consequently, a description of the environmental setting from the outer coast to the OCS is pertinent for addressing the overall study purpose.

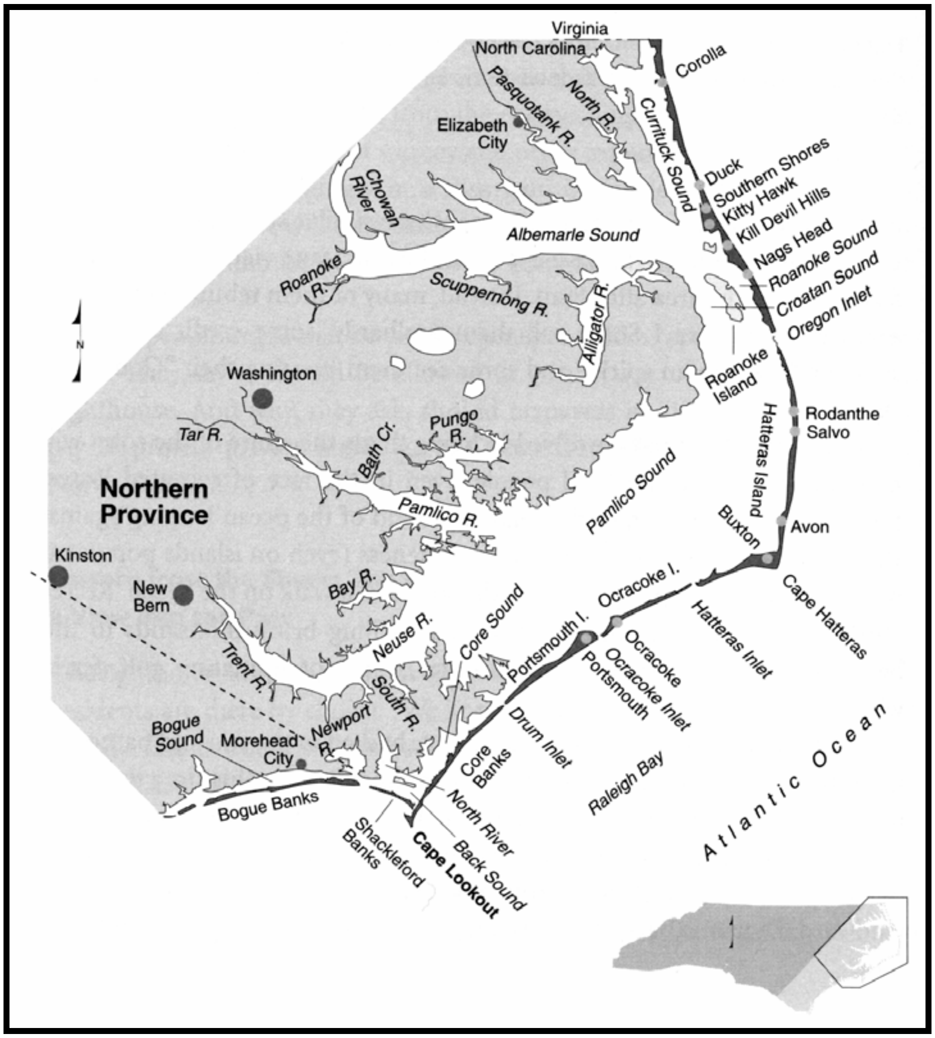

Figure 2-1. The northern coast Outer Banks of North Carolina (from Pilkey et al., 1998).

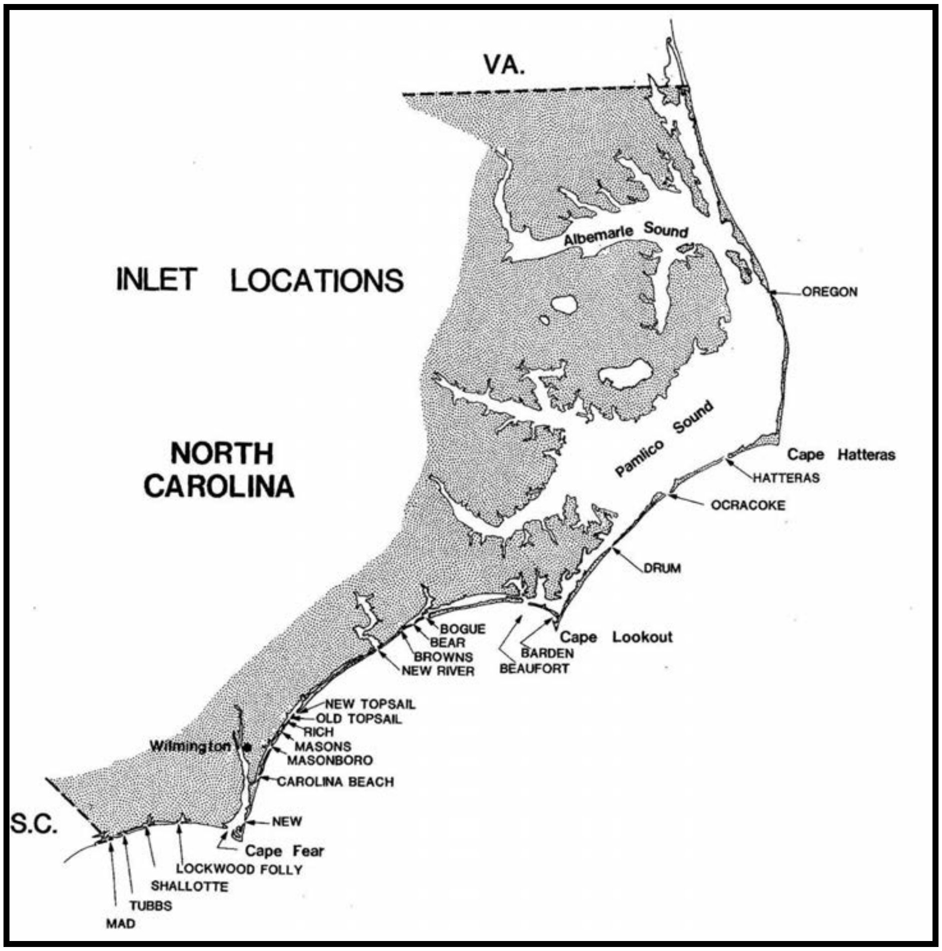

Figure 2-2. Inlet locations along the Outer Banks (Cleary and Marden, 1999).

Figure 2-3. Looking north from Oregon Inlet to southern Bodie Island.

Although Outer Banks beaches are transgressive and migrate westward at an average rate of about 1.4 m/yr (Inman and Dolan, 1989), estimates of shoreline recession vary with location (Figure 2-4). According to Inman and Dolan (1989), sea-level rise accounts for approximately 21% of shoreline recession; the remaining 79% is caused by washover, longshore transport, wind-blown transport, inlet deposits, and dredging. Maximum rates of net change are less than 5 m/yr, but the standard deviations of those rates are equal to or greater than the net rates. This indicates that there is large temporal uncertainty associated with these estimates. Variations in shoreline recession rates may be caused by underlying geology, and areas on top of old inlets are expected to be most vulnerable to erosion (Riggs et al., 1995).

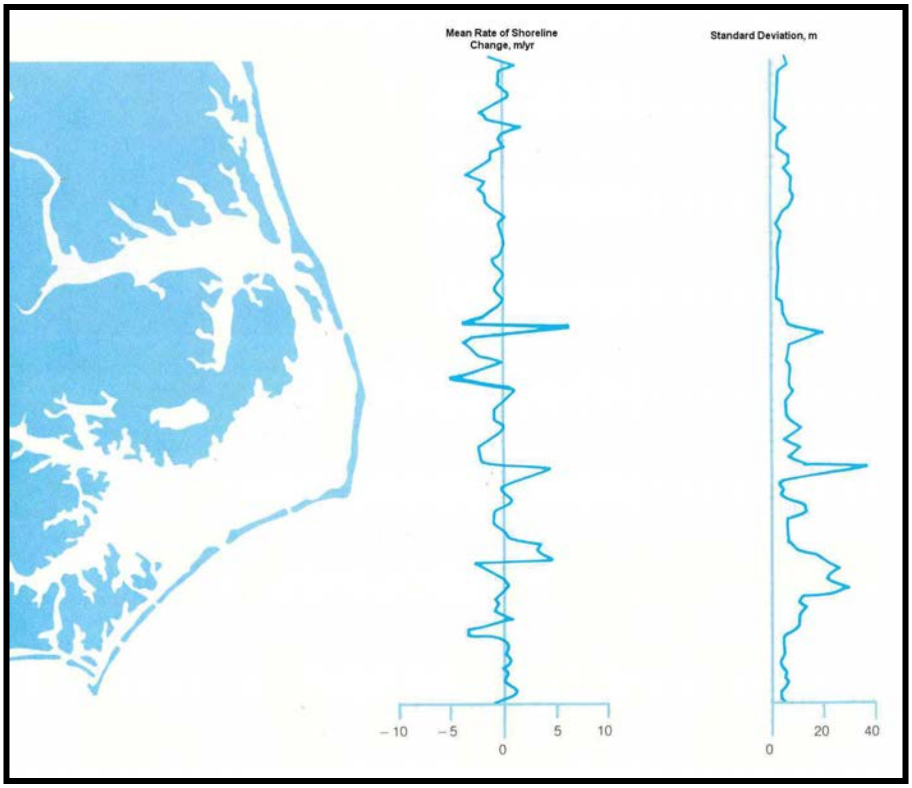

Figure 2-4. Shoreline change rate for the northern North Carolina barrier island coast (from Dolan and Lins, 1986).

The first settlers and vacationers arrived to the Outer Banks in 1663 and 1753, respectively (Dolan and Lins, 1986). Settlers typically lived near the sounds to avoid dangers associated with the ocean. It was not until after the Civil War that the ocean side began to be developed. In 1930, the first paved road was constructed on the ocean side of the barrier. The first of many attempts to stabilize the Outer Banks occurred in 1830 when Ocracoke Inlet was dredged (Dolan and Lins, 1986). Dredging continued for seven years until the channel began infilling as fast as it could be dredged. Efforts to preserve the Outer Banks began in the early twentieth century when the National Park Service and the Civilian Conservation Corps planted vegetation and constructed sand fences over 185 km of beach (Figure 2-5). In 1935, the Cape Hatteras National Seashore (121 km^2) was authorized. Later in 1966, 99 km^2 were authorized for the Cape Lookout National Seashore.

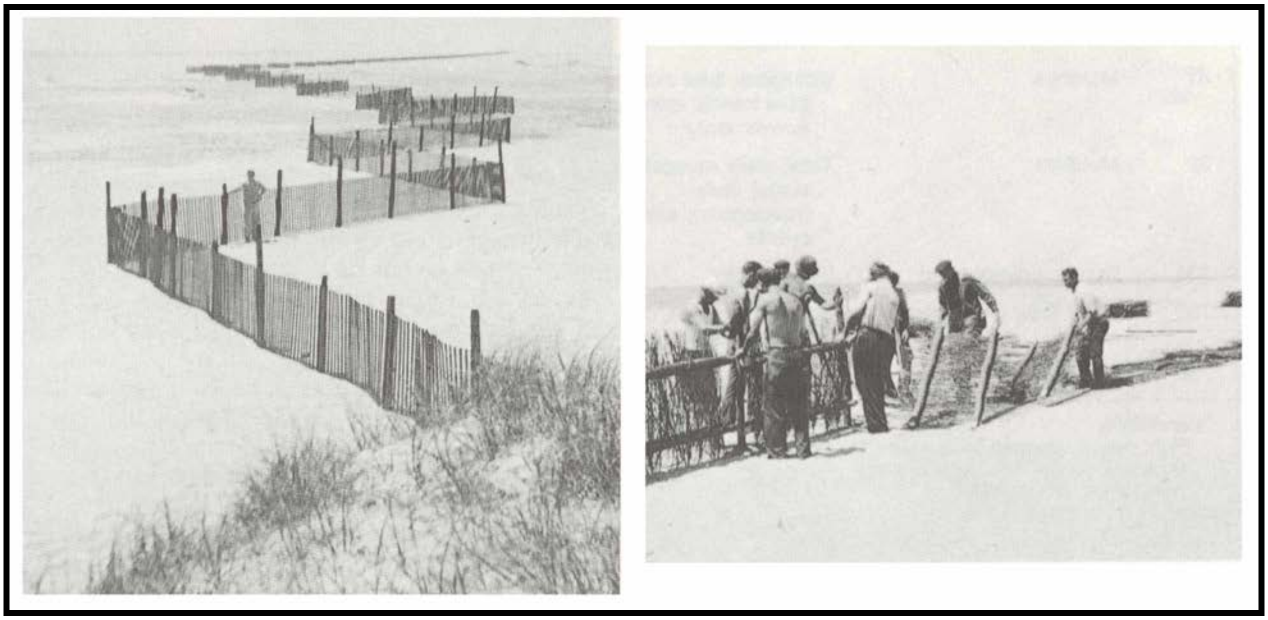

Figure 2-5. Sand fences constructed by the Civilian Conservation Corps along the Outer Banks in 1933 (from Dolan and Lins, 1986).

The barrier beaches of North Carolina are vulnerable to shoreline erosion due to high wave energy, currents, and sea-level rise (Inman and Dolan, 1989). In fact, Inman and Dolan (1989) state that North Carolina has the highest rate of sea-level rise along the east coast of the United States (35 to 40 cm/century; Figure 2-6). For the immediate study area offshore Bodie Island, mean sea level (MSL) elevations measured at the U.S. Army Corps of Engineers (USACE) Field Research Facility (FRF) in Duck, NC indicate an 8.4 cm rise between January 1986 and September 2002 (Figure 2-7), or 0.5 cm/year.

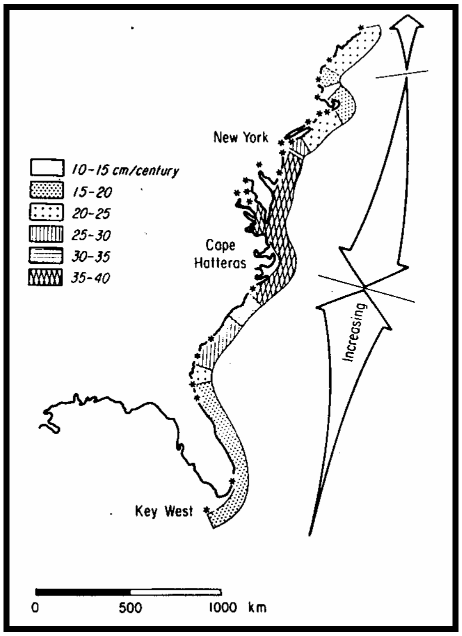

Figure 2-6. Rates of sea level rise along the east coast of the United States (from Inman and Dolan, 1989) based on Aubrey and Emery (1983).

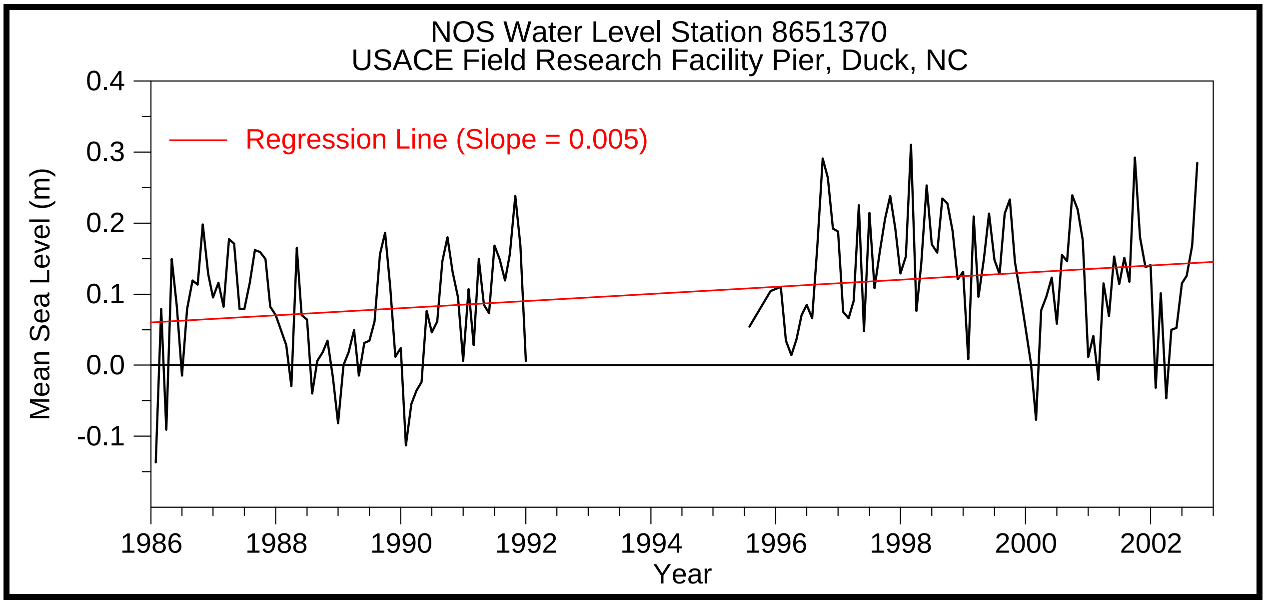

Figure 2-7. Trend for Mean Sea Level (MSL) elevations at Duck, NC (NOAA Station Number 8651370), 1986 to 2002.

2.1 OFFSHORE SEDIMENTARY ENVIRONMENT

Sand deposits from paleo-fluvial systems, modern inlet systems, and physical reworking of beach and shoreface environments by fluctuating sea level and modern processes have molded the bathymetry offshore Dare County (Swift et al., 1972; McBride and Moslow, 1991). Sea level variations during the Holocene created complex offshore topography, such as shoreface-attached and shoreface-detached sand ridges (Swift et al., 1972). Shoreface ridge origin on the northern North Carolina shelf and elsewhere has been debated for years (e.g., Swift et al., 1972; Stubblefield et al., 1984; McBride and Moslow, 1991; Snedden et al., 1994), with primary emphasis on modern shelf sediment transport processes and geologic controls associated with Holocene shoreline and inlet shoal deposits. Sand ridges offshore Bodie Island generally are oriented obliquely to the shoreline in a north-south direction.

Barrier island morphology of the Outer Banks is controlled by underlying geology (Hine et al., 1979; Riggs et al., 1995). The barriers are perched on pre-Holocene stratigraphic units (Riggs et al., 1995) that can roughly be divided into two geologic provinces at Cape Lookout. Islands north of Cape Lookout overlie Quaternary deposits, and barriers south of Cape Lookout are on Tertiary and Cretaceous deposits (Riggs et al., 1995).

2.1.1 Seabed Morphology

The continental shelf varies in width from 120 km offshore Cape Henry to 40 km offshore Cape Hatteras (Inman and Dolan, 1989). The continental break is shallowest near Cape Hatteras, with depth increasing to the north (Shideler and Swift, 1972). The continental shelf north of Cape Hatteras has been deeply eroded by ancient river systems, such as the Albemarle, during periods of lower sea level (Swift et al., 1972).

Sand ridges along the inner and outer shelf that are obliquely oriented with respect to the shoreline are dominant features in the offshore environment (Swift et al., 1972). On the inner shelf, ridges have a spacing of about 2.1 km and a height of 2 to 10 m, whereas on the outer shelf, ridge spacing is about 6 km (Swift et al., 1972). Outer shelf ridges are less complex and sub-parallel to the shelf break. Shoreface ridges may alter sediment transport processes on the shelf by guiding transport parallel to their crests (Swift et al., 1972). Large shoal features are asymmetrical, indicating longshore transport to the south. The origin of ridges offshore North Carolina is uncertain, but three hypotheses relating their formation to shoreline retreat have been proposed (Swift et al., 1972; McBride and Moslow, 1991):

- Sand ridge development by detachment of shoreface during sea level rise;
- Inlet associated shoal-retreat ridges; and
- Cape-associated shoal-retreat ridges.

Sand ridge development by shoreface detachment may occur as sea level rise accelerates and barrier transgression increases (Swift et al., 1972). If the base of the shoreface is below the region of active wave energy, it may be stranded as the barrier migrates landward. Cape associated shoals will form when there is significant longshore transport, high wave energy, and a stabilizing headland from which the shoal develops (Swift et al., 1972). At the headland, longshore currents converge due to wave refraction around the headland, and littoral sediment will be deposited offshore. The seaward end of a cape-associated shoal often is segmented by spill over lobes that dissect the shoal during storms when water piles up on one side of the ridge. Diamond Shoals off Cape Hatteras is an example of a cape-associated ridge.

Platt Shoals, seaward of Nags Head and within the sand resource study area, and sand ridges off False Cape are inlet associated ridges. Historical inlets, such as Old Currituck Inlet, deposit sand as an ebb-tidal shoal. As the inlet migrates to the south and the barrier migrates landward, an elongate shoal develops at the orientation of the ebb-tidal delta retreat path (Figure 2-8; McBride and Moslow, 1991). When inlets close from excessive longshore sand transport, sand is reworked by Holocene processes into shoreface sand ridges.

Shoals on the North Carolina continental shelf north of Cape Hatteras up to 5 km long and several meters thick were characterized by Snyder (1993) with high-resolution, shallow seismic profiles (Figure 2-9). Similar features were identified by Hoffman (1998) and Boss and Hoffman (2001) in seismic and vibracore data collected by the NCGS (Figure 2-10). Snyder (1997) and Boss et al. (1999) documented small-scale bedforms on the shoreface between Oregon Inlet and Duck with sidescan sonar profiles. Boss et al. (1999) defined five principal seafloor types based on the acoustic character of the seafloor from sidescan sonar profiles: 1) a relatively weak acoustic return producing a generally uniform, light gray sonar record; 2) a moderate to strong acoustic return producing a medium-to-dark gray sonar record; 3) mixed weak and strong acoustic returns producing a sonar record with mixed light gray and medium-to-dark gray areas (termed “patchwork” pattern); 4) a relatively weak acoustic return with small areas of stronger (darker) reflections (termed “pock-marked” appearance); and 5) potential hard bottom or live bottom identified by the presence of small scarps.

Light gray sonograms (weak acoustic return) were found to be the most common acoustic signature observed by Boss et al. (1999) (Figure 2-11). Typically, these areas are associated with north-south trending bathymetric highs that average about 2.8 m thick. Sediment samples from cores for this seafloor type indicate that it is predominantly fine sand with zones of medium-to-coarse sand and shell near the base of shoals (Boss et al., 1999). Sonograms with medium-to-gray tones are the next most common type (Figure 2-12). A comparison of surface type relative to bathymetry and seismic profiles indicates that these deposits exist in troughs between bathymetric highs in the southern part of the study area. Surface texture is primarily medium-to-coarse sand with gravel-sized material and ripples with 1 to 1.5 m spacing (Boss and Hoffman, 2001).

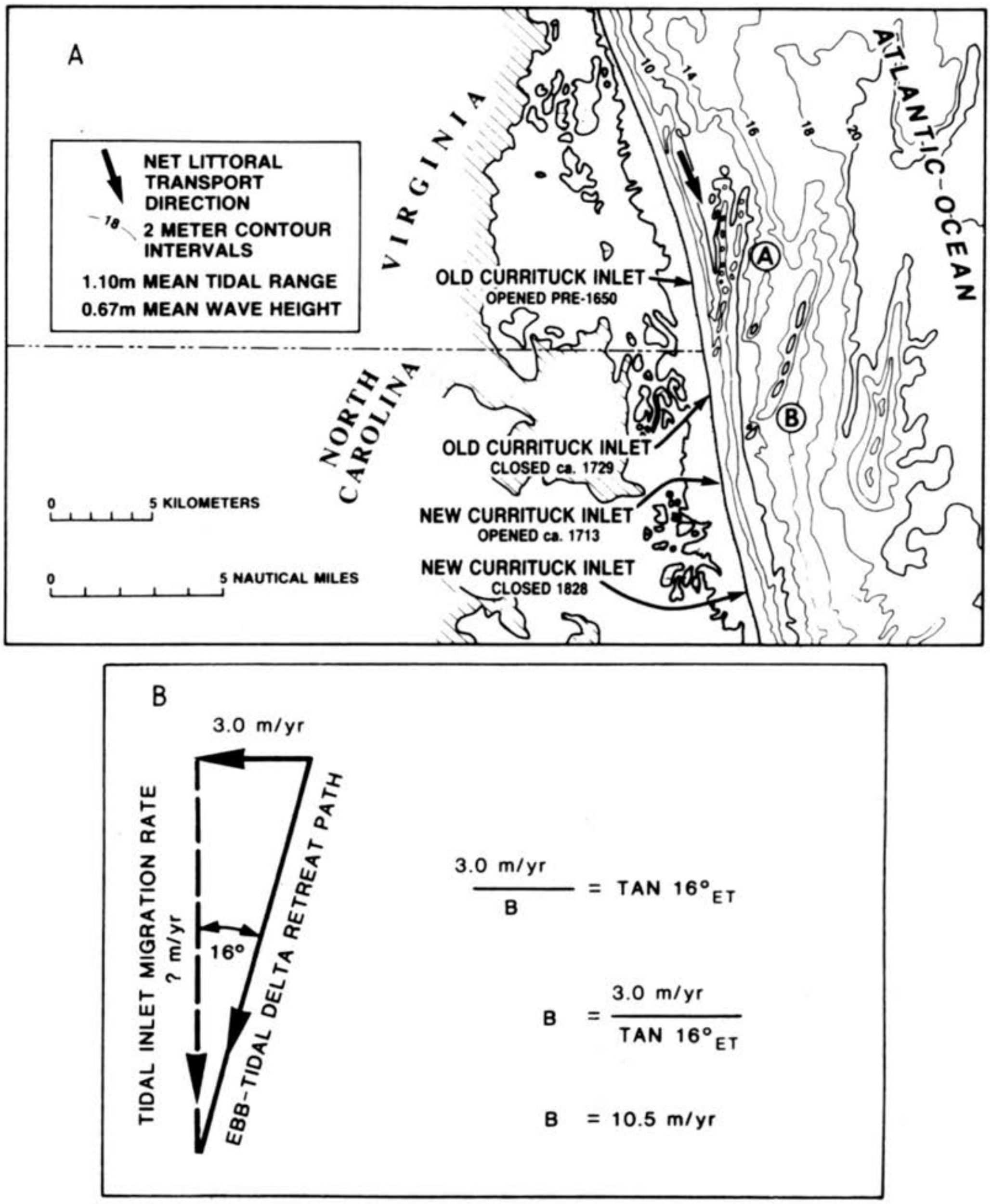

Figure 2-8. Migration of Old Currituck Inlet in relation to False Cape Shoals (from McBride and Moslow, 1991).

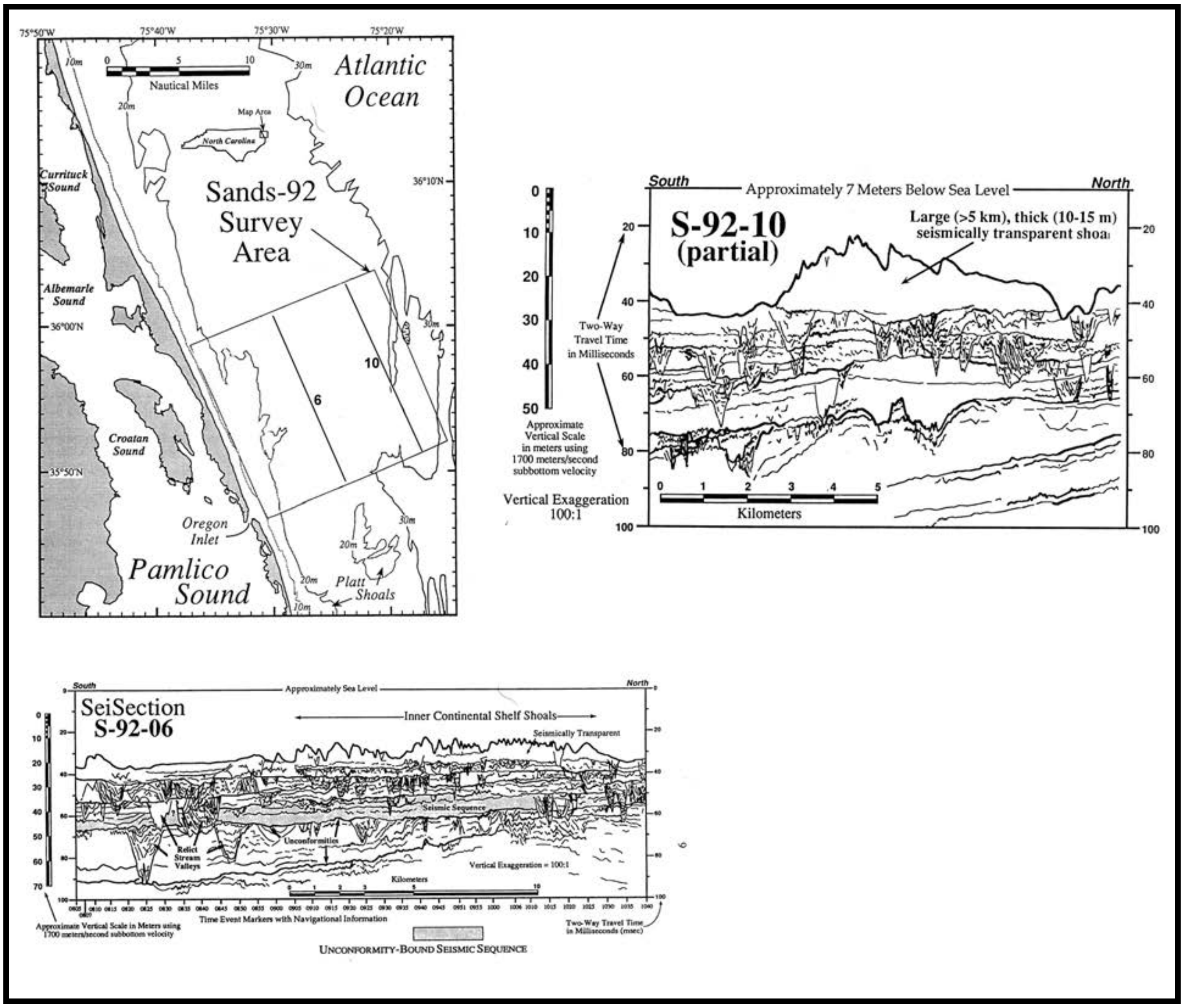

Figure 2-9. Seismic profiles in the vicinity of Platt Shoals (from Snyder, 1993).

The patchwork sonogram is a mixed weak and strong acoustic return that primarily is associated with slopes between bathymetric highs and lows (Figure 2-13). Boss et al. (1999) observed this seafloor type grading upslope to fine sand and downslope to medium-to-coarse sand and gravel. The location of this seafloor type suggests that it may result from fine sand transport downslope from ridges partially covering coarse sediment exposed in troughs. Pock-mark sonograms (Figure 2-14) also are caused by mixed acoustic signatures, but they are restricted to the northern portion of the study area. This seafloor type exists predominantly in areas that are relatively flat-lying at depths >20 m. Boss et al. (1999) state that it represents resistant stratum outcropping on the seafloor associated with sediment deposited within the Roanoke-Albermarle paleofluvial channel system. Vibracores from this area are predominantly mud with lenses and beds of fine sand (Boss and Hoffman, 2001). The final seafloor type may be associated with hard bottom deposits (Figure 2-15). Very few near-vertical features similar to hard bottom signatures reported from Onslow Bay (Riggs et al., 1998) were identified by Boss et al. (1999) within the study area.

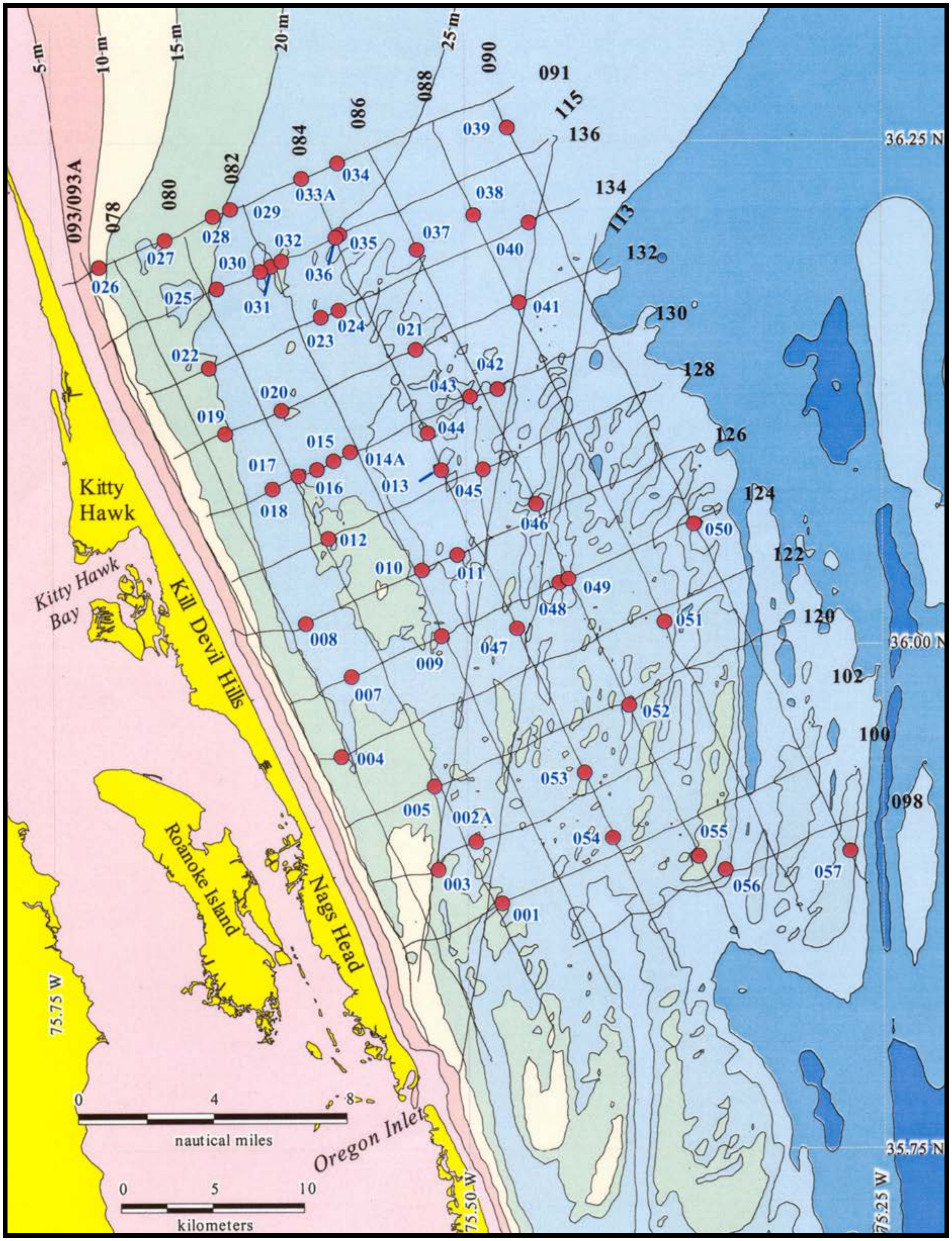

Figure 2-10. Distribution of seismic and side scan sonar track lines (black lines) and vibracore locations (red-filled circles) offshore Dare County, NC (from Boss and Hoffman, 2001).

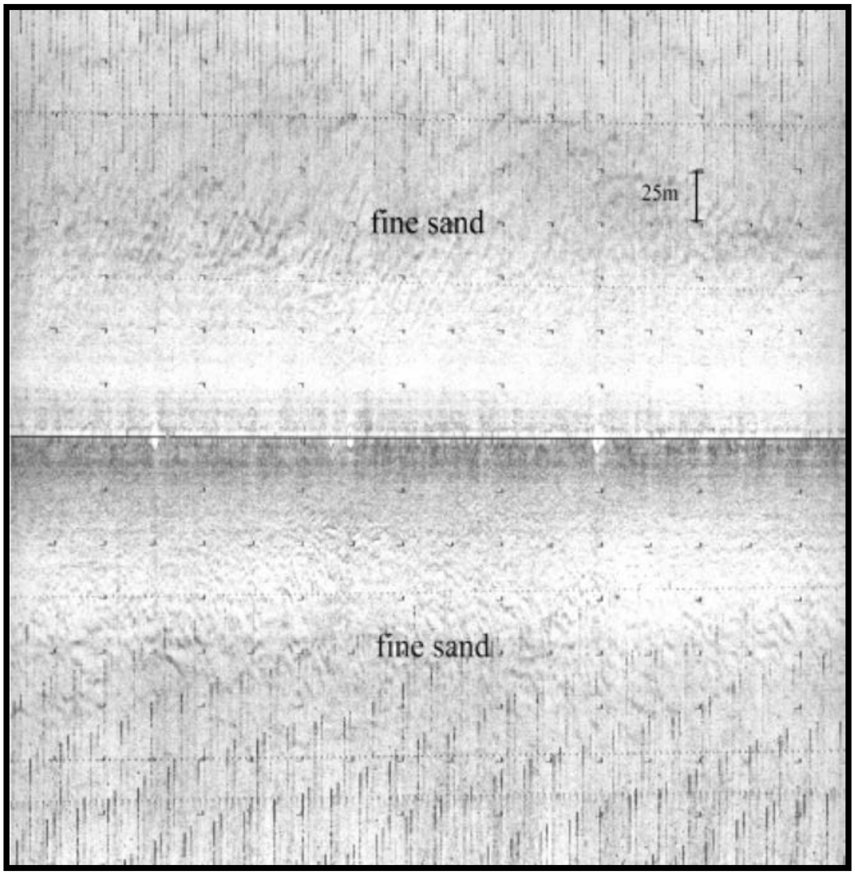

Figure 2-11. Sonogram illustrating smooth, light gray (fine sand) surface (from Boss et al., 1999).

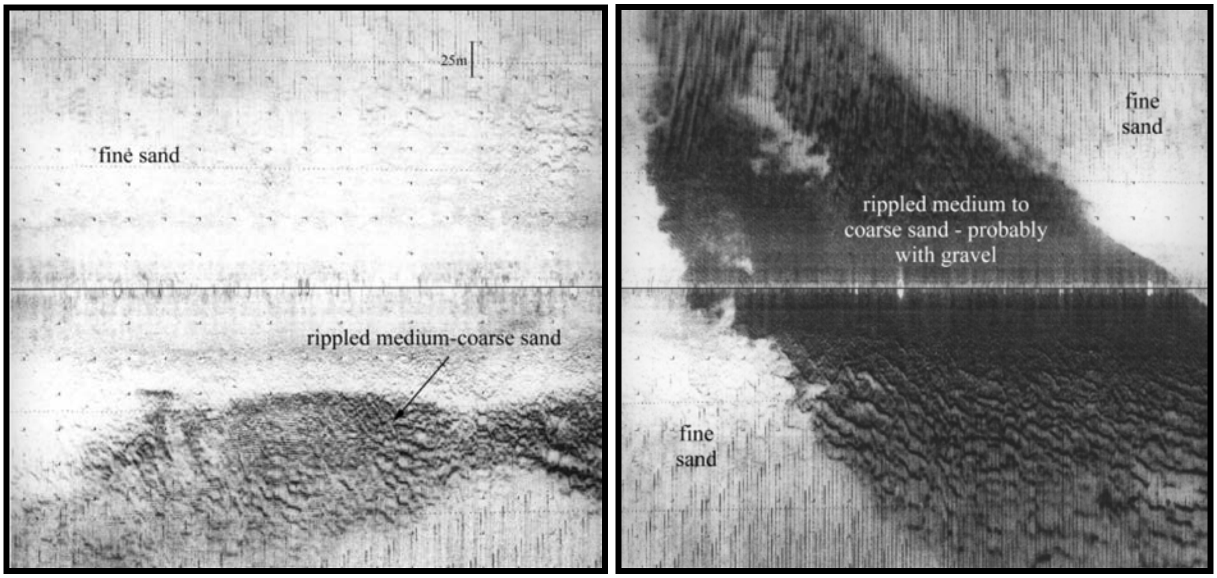

Figure 2-12. Sonograms illustrating light gray and rippled medium-coarse sand (dark gray) surface (from Boss et al., 1999).

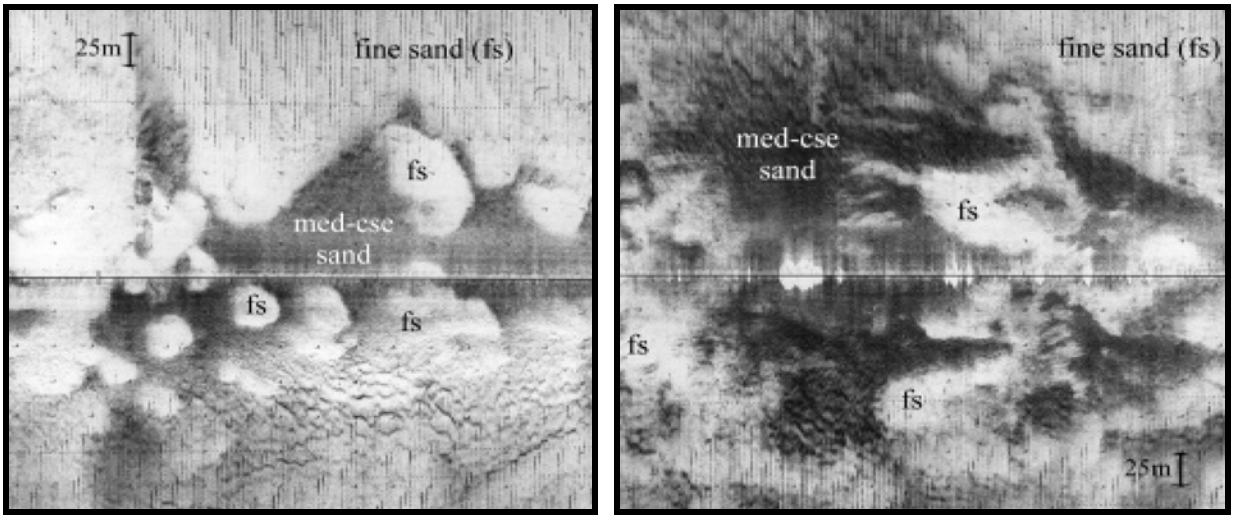

Figure 2-13. Sonograms illustrating patchwork surface pattern; mix of fine and medium-coarse sand on slopes of ridges (from Boss et al., 1999).

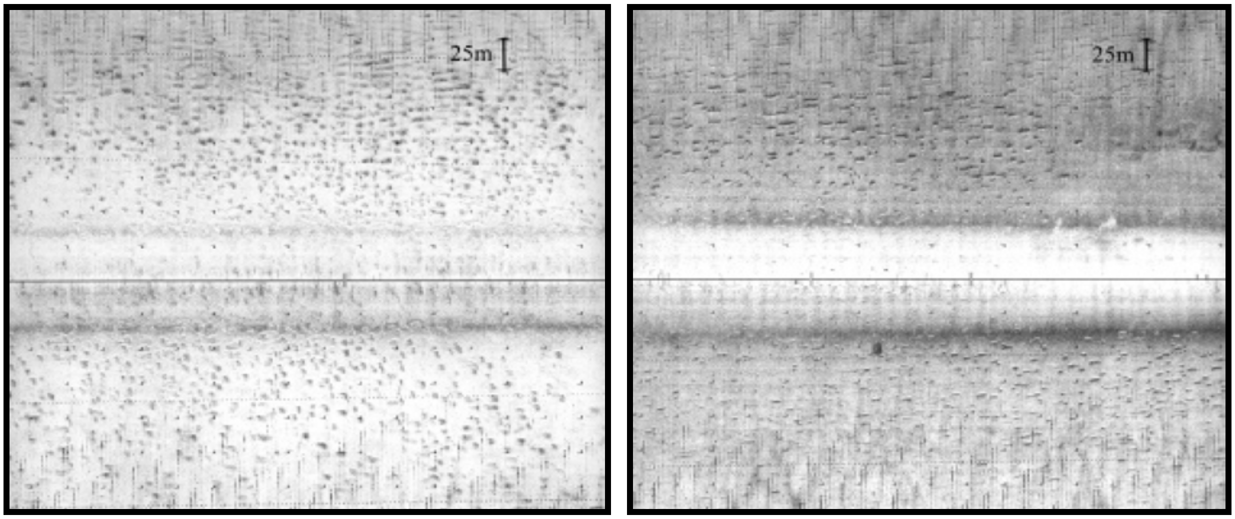

Figure 2-14. Sonograms illustrating pock marked surface pattern existing in the northern part of the study area associated with outcropping mud and sand lenses (from Boss et al., 1999).

Overall, the study area can be divided into two general regions based on surface texture. The southern area is characterized by north-south oriented sand ridges with troughs underlain by medium-to-coarse sand and gravel (Boss et al., 1999; Boss and Hoffman, 2001). The northern area contains relatively featureless bathymetry underlain by predominantly mud facies with fine sand beds and lenses. Throughout the study area, the areal coverage by hard bottom is relatively small (Boss et al., 1999). Figure 2-16 illustrates the distribution of sediment types relative to survey lines, illustrating a predominance of fine sand associated with ridges in the southern portion of the study area.

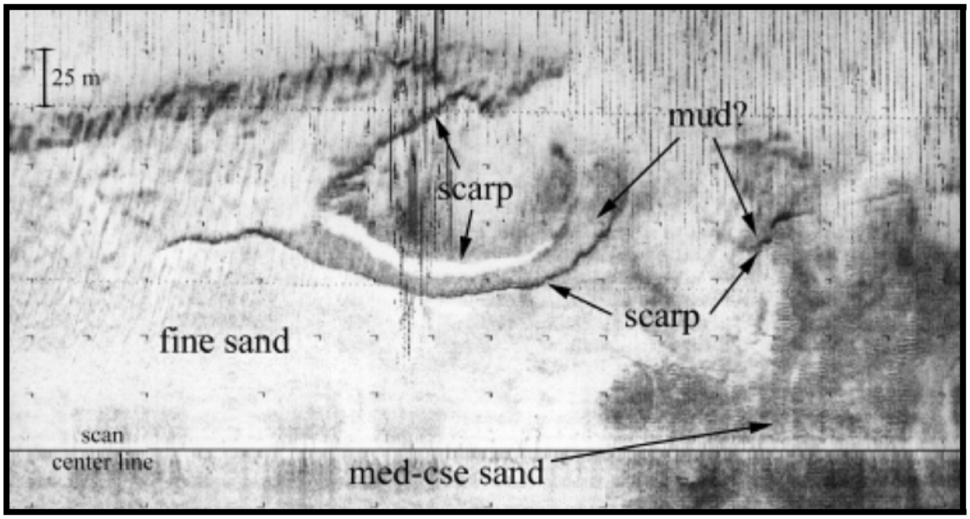

Figure 2-15. Sonogram illustrating scarps that occur occasionally on the shelf surface. Boss et al. (1999) interpreted these features as resistant material, probably cohesive mud, exposed on slopes (from Boss et al., 1999).

2.1.2 Surface Sediment

Sediment offshore North Carolina has four principal sources: erosion of barriers, detrital sediment from rivers, biogenous remnants of marine organisms, and relict sediments from pre-Holocene environments (Inman and Dolan, 1989). Review of current literature suggests that relict sediment and erosion of the Outer Banks are the primary sources of sediment for beach and nearshore environments (Riggs et al., 1995).

Sediment distribution on the continental shelf is patchy, indicating that sediment transport is locally variable, possibly limited by the presence of large-scale sand ridges (Riggs et al., 1995). Fine-grain sediment may be transported over long distances because it can be carried in suspension over the top of sand ridge crests (Riggs et al., 1995). North of Cape Hatteras, sediment contains abundant heavy minerals and quartz, and it is finer than sediment south of the Cape (Grosz et al., 1990). For the Roanoke-Albermarle paleofluvial channel system, estuarine mud crops out on the seafloor, and fluvial sands underlie the mud (Snyder, 1997b). South of Cape Hatteras, sediments are carbonate rich (Grosz et al., 1990).

Sediments farther offshore have been mapped with high-resolution sidescan sonar by the United States Geological Survey (USGS) (Figure 2-17). Areas of high backscatter (light areas) are sand and gravel, whereas areas of low backscatter (dark areas) are fine sand and silt. Platt Shoals (seaward of Nags Head) is a high backscatter area indicating that it is covered with sand and gravel. As stated above, sediment cores also have been collected outside the 3-mile Federal-State boundary for evaluating potential sand resources at and adjacent to Platt Shoals (Hoffman, 1998; Boss and Hoffman, 2001). As stated by Boss et al. (1999) and illustrated in Figure 2-16, fine sand surface texture predominates in the southern portion of the study area, and the percent of mud increases to the north.

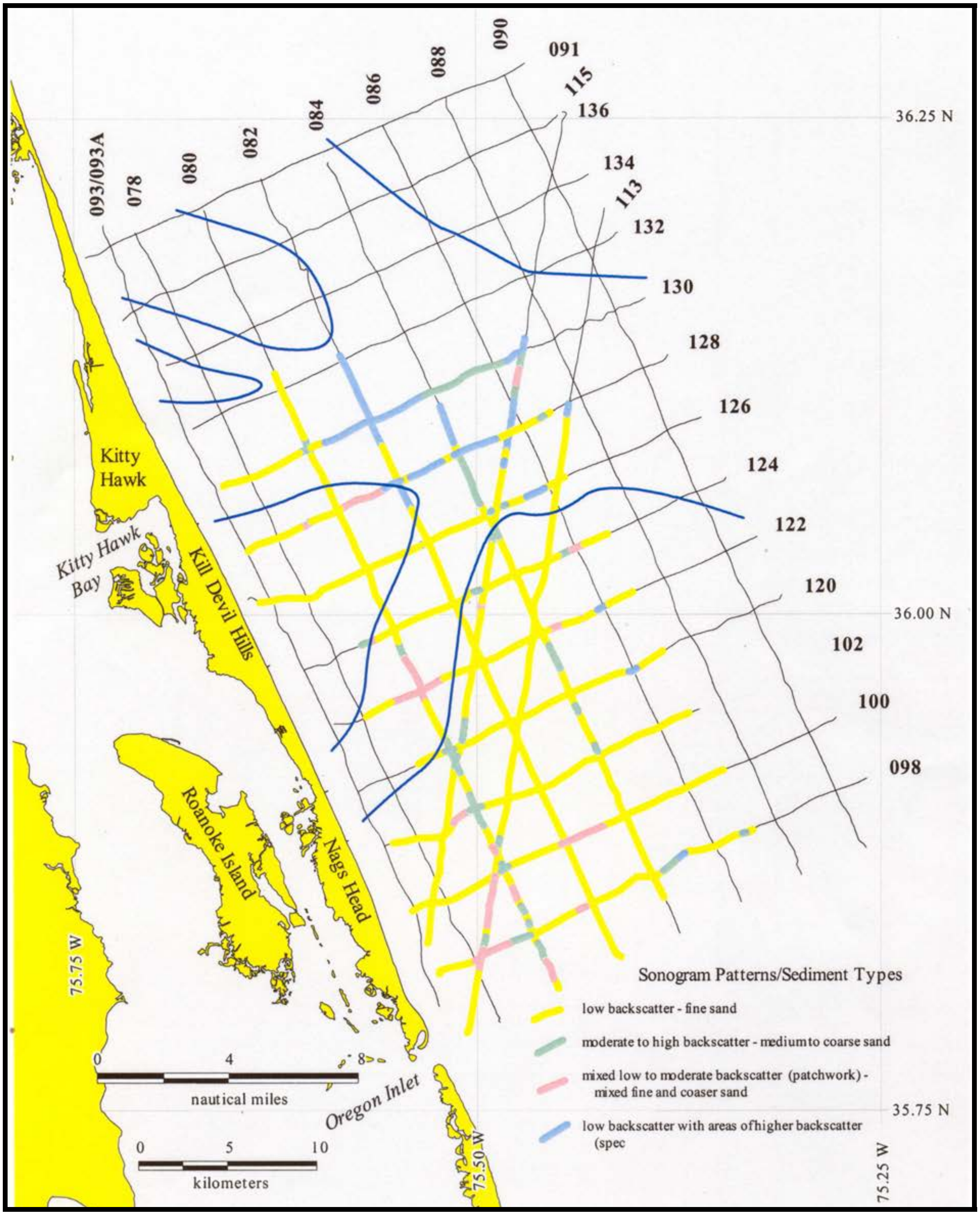

Figure 2-16. Distribution of primary sediment types as determined from sonogram patterns in the study area (from Boss and Hoffman, 2001).

Figure 2-17. Sidescan sonar of the northern coast of North Carolina (from USGS, 2001).

2.1.3 Subsurface Deposits

The underlying geology of the Outer Banks and adjacent offshore regions consist of heterogeneous, tabular lithostratigraphic units created by multiple cycles of sea level rise and fall (Riggs et al., 1995; Snyder, 1997a; Boss et al., 2002). During lowstands in sea level, fluvial systems are excavated in the exposed continental shelf, creating paleodrainage systems (Figure 2-18). As sea level rises, fluvial valleys are inundated and fluvial sedimentation moves landward many kilometers, creating shallow marine shelf environments dominated by fine to medium sand reworked from fluvial deposits (Riggs and Belknap, 1988; Riggs, 1996; Boss et al., 2002). This cycle of sea level rise and fall has created a complex subsurface off the coast of North Carolina (Shideler and Swift, 1972; Riggs et al., 1992). The influence of subsurface geology on the distribution and orientation of coastal deposits, including offshore ridge/shoal structures, has been described in detail by Riggs et al. (1995).

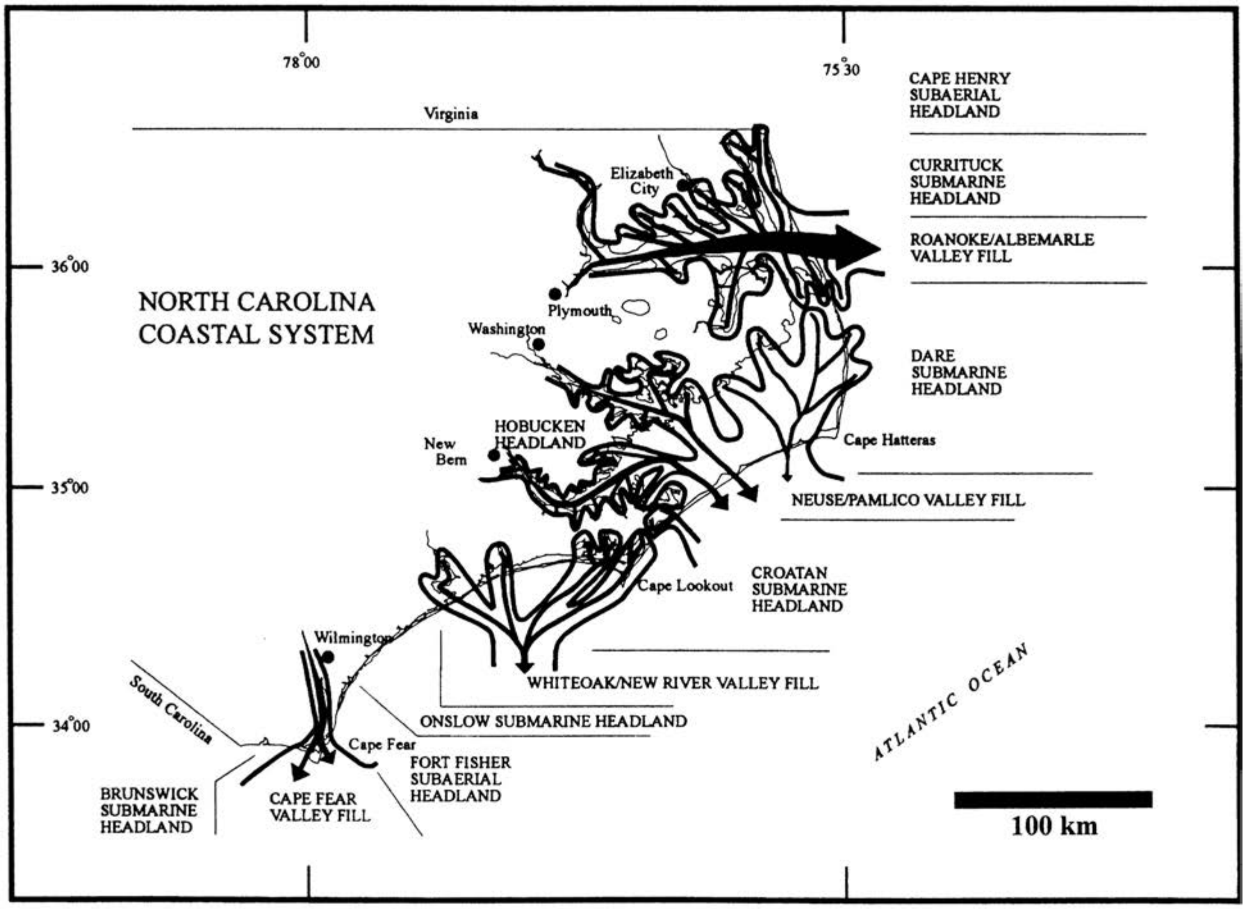

Figure 2-18. Paleodrainage system in coastal North Carolina (from Riggs et al., 1995). The area of greatest interest for this sand resources study is the Roanoke-Albermarle drainage system.

Shideler and Swift (1972) described offshore subsurface deposits between Cape Henry, Virginia, and Cape Hatteras, NC. They identified four subsurface units: Tertiary, pre-Wisconsin and early Wisconsin, late Wisconsin, and Holocene. Of these units, Holocene sediments are of greatest interest for defining sand resources offshore Dare County, NC. The Holocene transgressive sand sheet covering the modern sea floor is the youngest stratigraphic layer. These sands originate from eroding barrier islands. This unit truncates the upper portion of the late Wisconsin unit; the bottom reflector is 19 to 39 m below sea level (average 26 m) and 0 to 12 m below the sea floor (average thickness is 5 m). The Holocene unit is close to horizontal, dipping only 0.34 m/km to the east (Shideler and Swift, 1972). This sand sheet has been reworked by Holocene processes to form modern sand ridge features offshore North Carolina.

A detailed geophysical analysis of shoreface geology was completed by Boss and Hoffman (2001) and Boss et al. (2002) for offshore waters from Oregon Inlet to Duck, NC using single-channel, high-resolution seismic reflection and sidescan sonar profiles (Figure 2-10). Five mapped units were identified within the upper 70 m of the shelf stratigraphic succession. All but the top unit gently dip to the east-southeast (0.4 to 0.6 m/km) and have tabular geometry. The uppermost stratigraphic unit is composed of fine-grained fluvial/estuarine sediment that back-filled incised streams during early Holocene sea-level rise. Three-dimensional mapping of the base of this stratigraphic unit indicates its origin from fluvial incision of the continental shelf during lowered sea level (Figure 2-19; Boss et al., 2002). This fluvial feature, referred to as the

Roanoke-Albermarle Channel (RAC), is the dominant subsurface feature off the northern coast of North Carolina (Riggs et al., 1995; Snyder, 1997a; Snyder, 1997b; Boss et al., 2002). The RAC is an ancestral branch of the Chesapeake Bay watershed formed during the Wisconsin Ice Age 14,000 to 18,000 years ago when sea level was about 91 m lower than present (Boss et al., 2002). Figure 2-20 shows the cross-sectional extent of the channel deposit, where R1 is the bottom seismic reflector of the deposit. The maximum width of the channel is about 13 km (Boss et al., 2002). The lower boundary (R_1) of this unit is 20 to 50 m below sea level. The RAC is mostly fluvial sand that would be ideal for beach fill. Unfortunately, this resource may be access limited because estuarine muds overlie the sand (Snyder, 1997a).

Seismic unit S_2 encompasses sediment between reflector R_2 and the seafloor (R_0; see Figure 2-20). This unit includes the surface and subsurface expression of ridges in offshore sand resource areas defined by Hoffman (1998) and Boss and Hoffman (2001). Boss and Hoffman (2002) described the base of unit S_2 as a widespread reflecting horizon that has been truncated by channel incision related to the formation of the RAC. Reflector R_2 has relatively low relief with an overall slope of approximately 0.05 m/km to the east-southeast (Figure 2-21). Maximum thickness of unit S_2 is about 17 m, and average thickness is approximately 6 m. Sand resources within this unit are most compatible with sand on Dare County beaches.

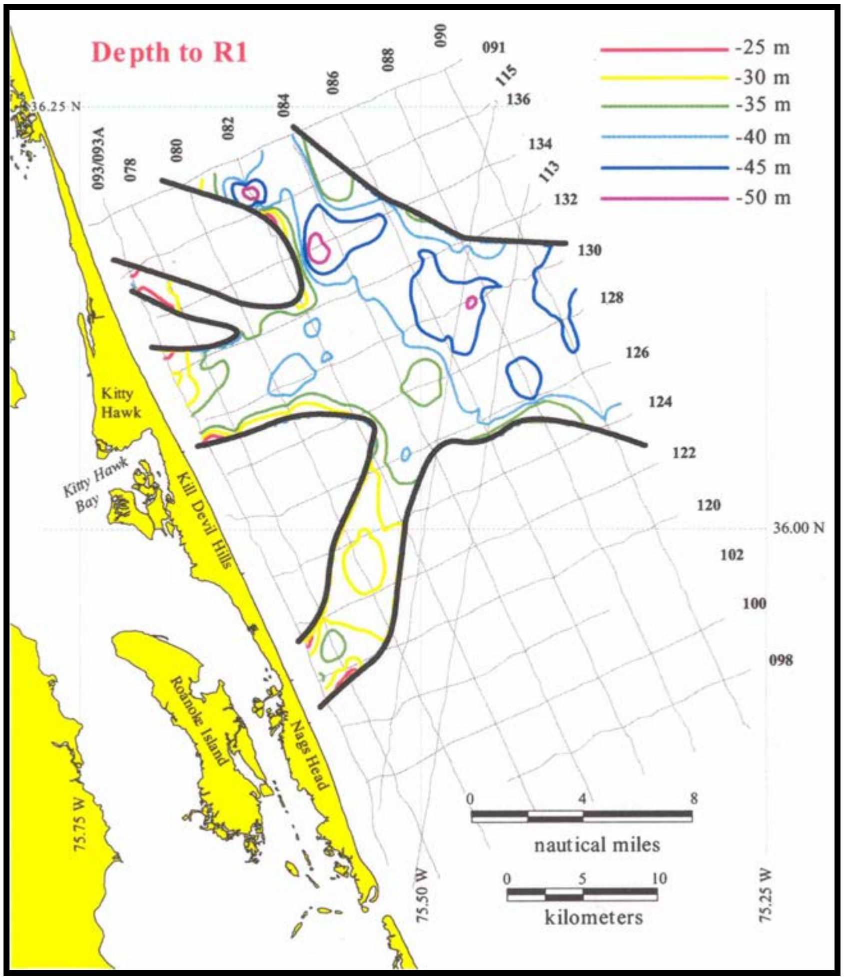

Figure 2-19. Areal extent and depth to seismic reflector R1 (from Boss and Hoffman, 2001).

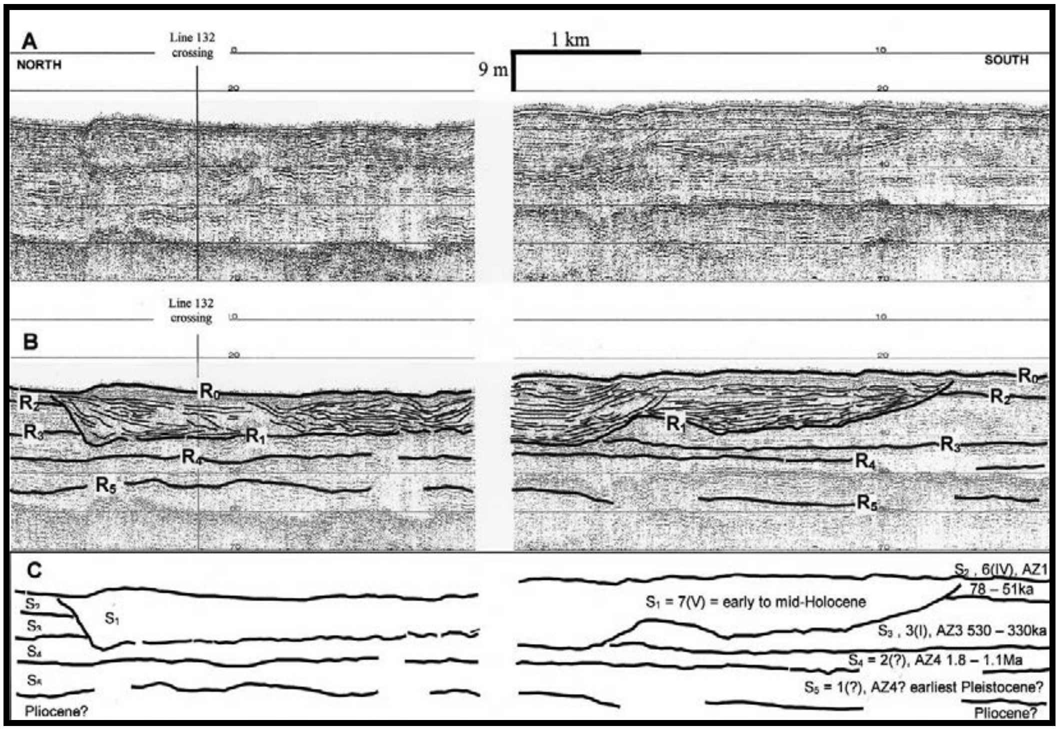

Figure 2-20. Portion of seismic reflection profile 080 near the intersection of line 132 illustrating the north (left) and south (right) margins of channel seismic facies S1 (from Boss et al., 2002).

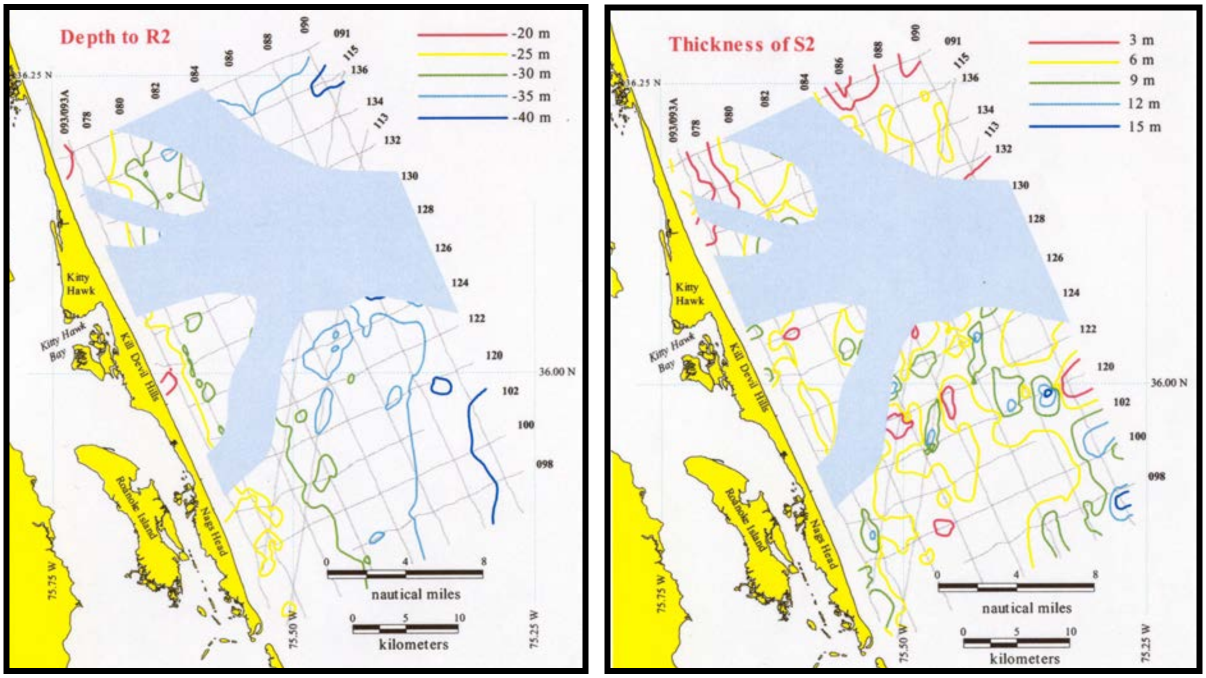

Figure 2-21. Structure contour map and isopach map for unit S_2. The channel system defined by reflector R_1 (shown in light blue) cuts through unit S_2 (from Boss and Hoffman, 2001).

2.1.4 Sand Resources

Potential sand resource areas in Federal waters (outside the 3-mile limit) are described by Hoffman (1998), Boss et al. (1999), and Boss and Hoffman (2001). Four primary locations were identified as potential sand resource areas (see Figure 2-22). In addition, three distal sand ridges also were suggested as secondary sites. Resource areas were delineated using shallow seismic profiles and vibracore data. Secondary sites are not considered economically feasible because of distance from shore and difficulties associated with deep water dredging (Hoffman, 1998). However, as dredging technology improves, these sites may provide an additional sand source to meet North Carolina beach replenishment needs.

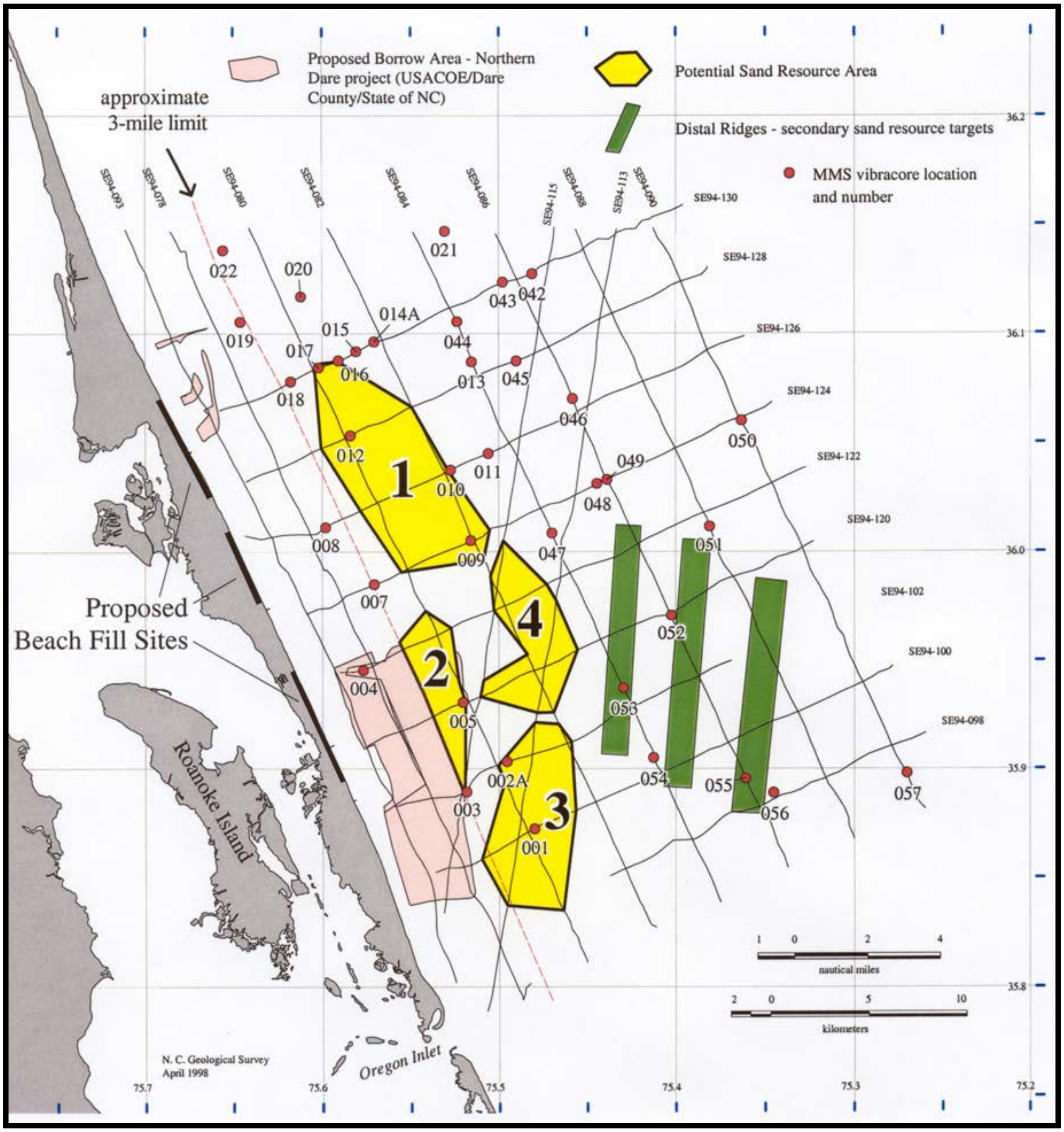

Figure 2-22. Diagram illustrating geological data and identified potential sand resource areas (from Hoffman, 1998).

Most potential sand resource areas delineated by Hoffman (1998) and Boss and Hoffman (2001) are located south of the RAC. Area 1 is the exception, as it is partially truncated to the northwest by the RAC (Boss et al., 1999; 2002). Areas 2, 3, and 4 are associated with north-south oriented sand ridges (Boss et al., 1999); Area 2 encompasses the distal part of Platt Shoals. Ripple bedforms identified at each of the resource areas indicates that the surface sand is mobile. Sand resource areas were identified by Hoffman (1998) and Boss and Hoffman (2001) by delineating a transparent seismic facies throughout the study area. Figure 2-23 illustrates three seismic cross-sections from Hoffman (1998) through the identified sand resource areas.

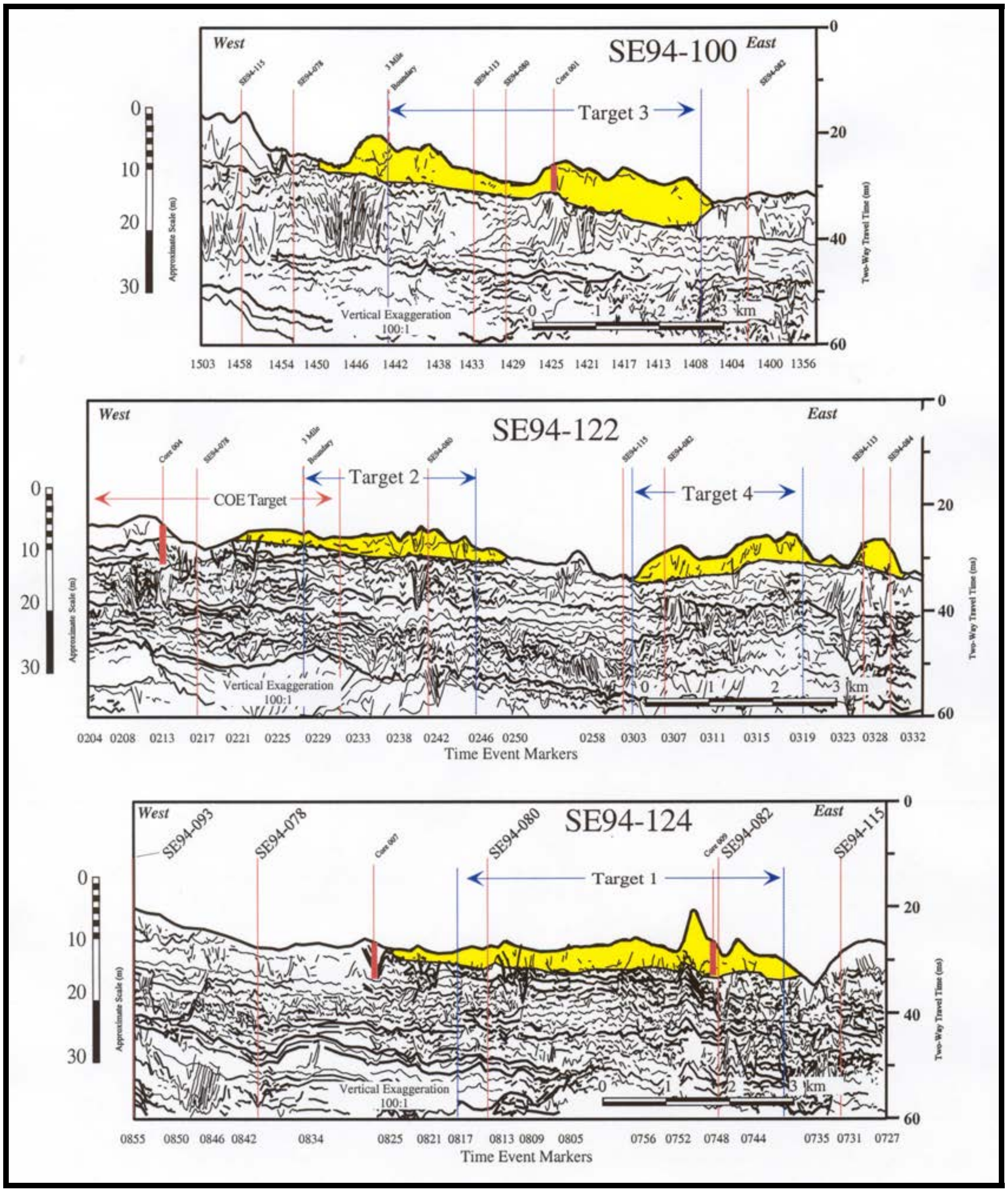

Figure 2-23. Selected seismic profiles crossing potential sand resource targets offshore North Carolina (from Hoffman, 1998). See Figure 2-22 for location information.

The seismic transparency of potential sand resource deposits may be attributed to homogeneous sediment where sufficient lithologic variation is lacking to produce seismic reflections or compacted sand at the surface of the deposit that might mask reflections in the upper portion of the unit (Hoffman, 1998). Vibracores obtained in the study area indicated that there were two major sediment types: a sandy lithofacies and a mud-prone lithofacies (Boss et al., 2002). The sand lithofacies (Type I) was divided into four subfacies: (IA) clean, laminated to massive quartz sand; (IB) coarse sand to gravel; (IC) normally graded, fining upward quartz sand; and (ID) reverse graded quartz sand (Boss et al., 2002). The mud-prone units (Type II) contained interbedded clayey sandy silt to silty sand (IIA) and mud-rich fine-to-medium sand (IIB). Mean grain size for Type I deposits was about 0.21 mm; Type II deposits averaged 0.11 mm. Figure 2-24 provides a representative image of each of these subfacies.

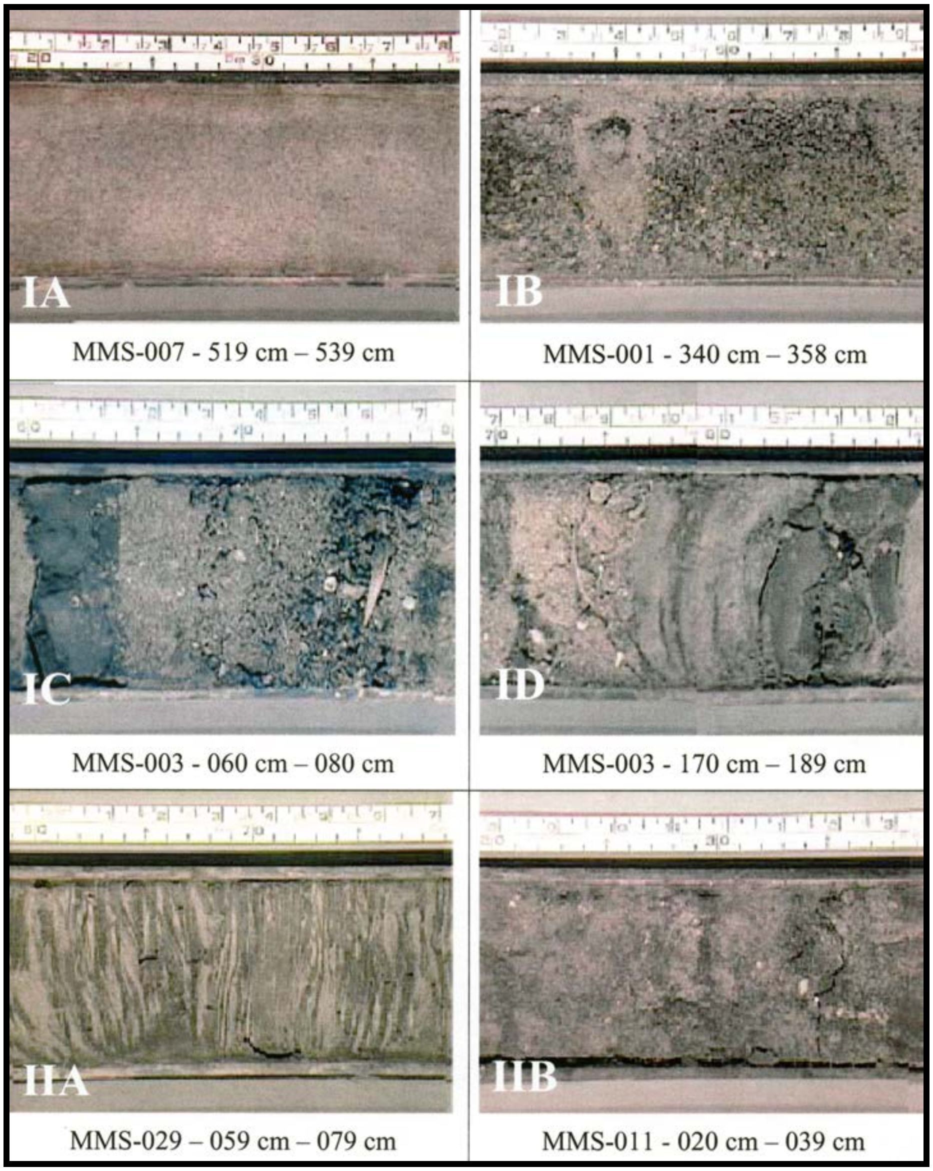

Figure 2-24. Illustration of the six representative lithofacies from offshore vibracores (see Figure 2-22 for core location; from Boss and Hoffman, 2001).

Hoffman (1998) targeted shoreface sand ridges (N-S oriented topographic highs) as the areas having the greatest potential as sand resource sites. Four primary resource areas were identified to contain at least 77 million cubic yards (mcy) of fine-to-medium sand. Boss and Hoffman (2001) included vibracore analysis and bathymetry data for updating the seismic stratigraphic framework in the offshore sand resource areas. Sand volume estimates at each of the four resource areas were revised to reflect information derived from vibracores; that is, identified offshore shoals, about 3-m thick and seismically transparent, were recognized as uniform light-gray features on sidescan profiles that contain approximately 300 mcy of predominantly fine sand (Table 2-1). Additionally, areas of medium-to-coarse sand usually were confined to the bathymetric troughs. A few small hard-bottom areas were identified but their coverage throughout the study area is minimal (Boss et al., 1999).

Table 2-1. Potential sand resource dimensions for the four primary sand targets (from Boss and Hoffman, 2001).

Potential Sand Resource Area	Area (million square yards)	Volume (million cubic yards)
Area 1	46.1	173.5
Area 2	9.5	44.9
Area 3	19.9	64.7
Area 4	12.5	23.2
Total	88.0	306.3

2.2 GENERAL CIRCULATION

The Mid-Atlantic Bight is the curved section of the continental shelf off the eastern United States extending between Cape Cod and Cape Hatteras. It is bordered by Nantucket Shoals to the north and Diamond Shoals to the south. These geomorphic features play an important role in defining the hydraulic regime and regional sediment transport patterns. The continental shelf of the Mid-Atlantic Bight is approximately 100 km wide from Cape Cod to Cape Henry, narrowing to approximately 37 km at Cape Hatteras (Uchupi, 1965; Hunt et al., 1977). The depth of the shelf break decreases from about 150 m south of Georges Bank to about 50 m off Cape Hatteras. The North Carolina shoreline from Cape Henry to Oregon Inlet is oriented approximately 20° counter-clockwise of north (Birkemeier et al., 1981). Alongshore currents flow northward toward 340°, or southward toward 160°.

General circulation is directly related to regional atmospheric surface pressure, wind stress, and regional density patterns along and across the shelf. As early as 1916, there was extensive evidence of mean annual southwestward flow along the continental shelf of the Mid-Atlantic Bight in response to north-northeast winds (Bigelow, 1922; Beardsley and Boicourt, 1981). At Cape Hatteras, south-moving shelf water turns seaward and is entrained by the north-flowing Gulf Stream (Bumpus, 1973). Based on measurements, mean annual current speeds typically range from 30 to 45 cm/s in the Mid-Atlantic Bight (Beardsley and Butman, 1974). Along the mid-shelf, between Hudson Canyon and Cape Hatteras, surface drifter releases showed southerly flow from 20 to 32 cm/s (Bumpus, 1973). Near-bottom flows along the shelf average 6 cm/s to the southwest (Bumpus, 1973; Butman et al., 1979; Chuang et al., 1979). Velocity magnitudes may be related to shelf width, increasing in speed to the south as the shelf narrows from Long Island to North Carolina (Hunt et al., 1977; Beardsley and Boicourt, 1981).

Outflow from major estuaries plays an important role in surface salinity and current patterns in the Mid-Atlantic Bight (Bigelow, 1922; Beardsley and Boicourt, 1981). Low-salinity waters of the Chesapeake Bay have been mapped as a narrow southward flowing band along the Virginia and North Carolina coasts, extending beyond Oregon Inlet at times of large bay outflows. Along-shelf low-salinity coastal currents were measured at speeds of 30 to 50 cm/s and decrease in magnitude with increasing distance from the coast (Boicourt, 1973).

The across-shelf flow was primarily density driven, evidenced by the increase in salinity with depth. The vertical salinity gradient created shelf circulation with a weak offshore component at the surface and a stronger onshore component near the bed. Sea-bed drifters on the middle and outer portion of the shelf of the Carolinas demonstrated northerly drift (offshore) at 1.5 to 2.5 cm/s (Boicourt, 1973; Bumpus, 1973). On the inner shelf and shoreface, bottom drift was onshore.

2.2.1 Tidal Currents

Tides in the Mid-Atlantic Bight are dominated by the M2 semi-diurnal component. Cook (2000) and Cook and Shay (2002) reported that 90% of tidal water elevation level change and 20 to 40% of horizontal current velocities are caused by the M2 component. A 12-year record of measurements at the Field Research Facility in Duck, NC shows an annual mean tide range of 0.9 m (Leffler et al., 1992) and a mean spring tide range of at least 1.2 m (Birkemeier et al., 1981). Three field experiments were conducted in Duck, NC over the period 1985 to 1988 under fair weather, moderate-energy, and storm conditions (Wright et al., 1991). During fair weather periods, winds were light (less than 5 m/s), waves were small (less than 0.6 m), and currents on the inner shelf were dominated by a weak reversing tidal component of approximately 10 cm/s (Wright, 1993). Although wave-induced orbital velocities tend to dominate during moderate energy events, tidal flows contributed to bed shear stress during high tide. During storm conditions, wind-generated mean flows and wave orbital velocities dominate over tidal currents. Near-bottom, along-shelf tidal currents of up to 20 cm/s have been measured in a water depth of 8 m, but were not seen in the current meter record measured at 17 m (Wright et al., 1991). In 1985 and 1987, cross-shore flow and sediment transport measured near Duck, NC tended to reverse with the tides. Weak offshore flow occurred at high tide, and stronger onshore flow prevailed during low tides (Wright et al., 1991).

2.2.2 Wind-Generated Currents

There is a strong correlation between north-northeast winds and currents along the Mid-Atlantic Bight (Xu and Wright, 1998). The mean annual wind stress is generally oriented toward the east and southeast in the Mid-Atlantic Bight and strongly coherent with southerly along-shelf flow (Beardsley and Boicourt, 1981); regional wind patters control 88% of the alongshore currents (Cudaback and Largier, 2001). Although strong winds in any direction will produce large swell, only northeast winds tend to generate strong alongshore currents. During a typical northeaster in 1991(moderate storm), measured mean currents were approximately 23 cm/s and orbital velocities were approximately 40 cm/s (Wright et al., 1994). Across-shelf flows during the northeast storm created seaward flow at 5 cm/s near the bed. Coupling between wind and water flow associated with northerly wind events parallel to isobaths of the Mid-Atlantic Bight create a coastward Ekman transport (Beardsley and Butman, 1974). North-northeast winds tend to enhance the coastal plume flowing out of Chesapeake Bay and favor seaward-directed, cross-shore, near-bottom flow (Xu and Wright, 1998).

Along-shelf flows were recorded by Lentz et al. (1999) for four months at locations 0.4, 0.8, 1.4, 5.3, and 16 km offshore Duck, NC (Figure 2-25). The observations show that currents

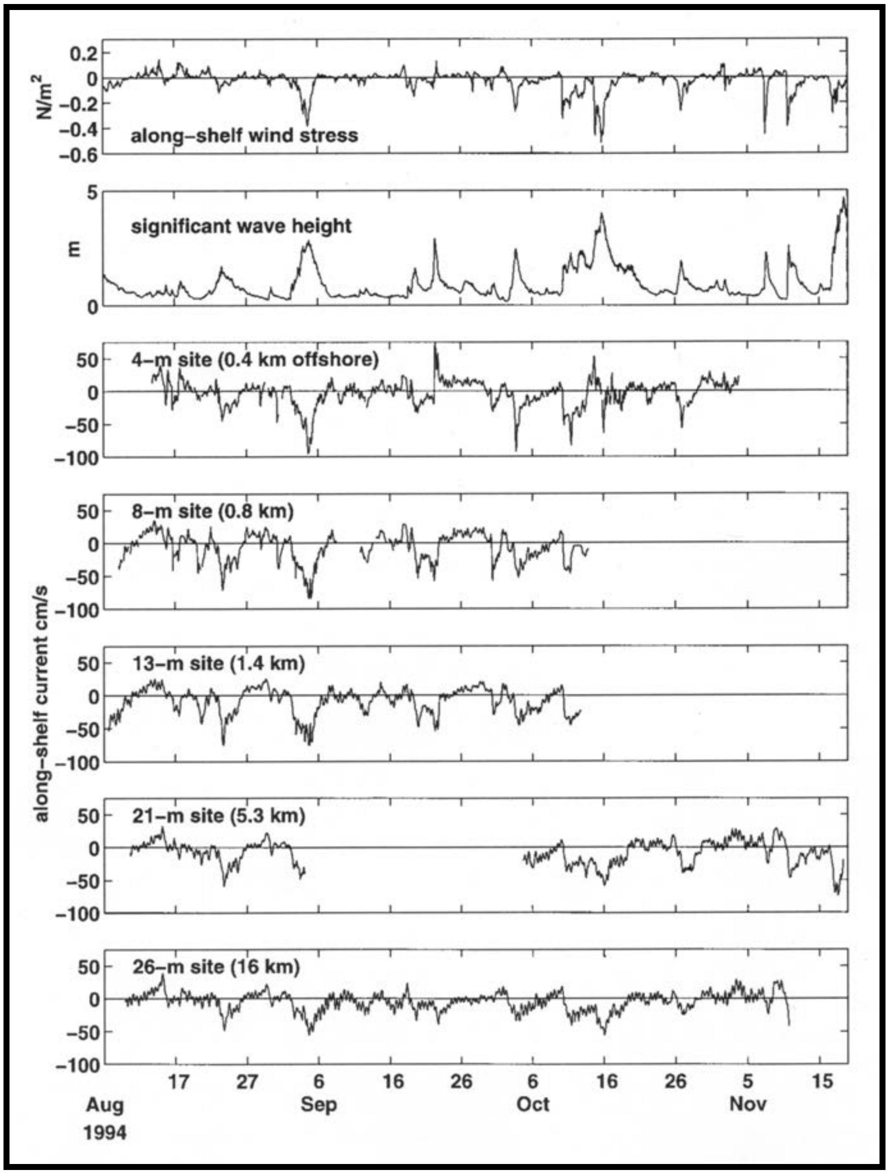

Figure 2-25. Time series of the along-shelf wind stress (negative is equatorward); significant wave height in 8-m water depth; and the subtidal depth-averaged, along-shelf current at the five mooring sites. Offshore distances of mooring sites are in parentheses (from Lentz et al., 1999).

were typically towards the south, and fastest currents were about 50 cm/s. On average, alongshore current velocities ranged from 4 to 10 cm/s, and cross-shore velocities were about 1 to 2 cm/s (Lentz et al., 1999).

Wind stress in summer months tends to be relatively weak and directed toward the northeast (Beardsley and Boicourt, 1981). Summer southwest winds can result in up-shelf flow for 1 to 3 months. Upwelling is observed along much of the Mid-Atlantic Bight during July and August following southwesterly winds (Boicourt, 1973; Bumpus, 1973). Reversal in wind stress creates a vertical shear due to an offshore increase in the mean density field, such that the strongest up-shelf flow tends to be greatest near the bottom (Beardsley and Boicourt, 1981).

2.2.3 Density-Driven Currents

Buoyant water masses, originating from the Chesapeake Bay, migrate south along the coast to North Carolina every 3 to 8 days (Rennie et al., 1999; Cudaback and Largier, 2001). Buoyant water travels south at a rate of 0.3 to 0.7 cm/s (Rennie et al., 1999). During periods of northerly winds, less dense (less saline) water in the Chesapeake Bay is confined to the bay by wind stress. As winds subside or turn to the south, buoyant water is released from the bay and flows down the coast. Additionally, northerly winds result in upwelling along the coast of North Carolina, while southerly winds produce downwelling. During downwelling, less saline water from the Chesapeake will move south and sink with downwelling currents. This results in the halocline moving above the thermocline. During upwelling, the remaining Chesapeake Bay water mass moves offshore and the halocline and thermocline return to the same position.

Mean southward flow of the Mid-Atlantic Bight seems to be driven primarily by an alongshore pressure gradient imposed at the shelf break (Beardsley and Boicourt, 1981). The pressure field is established by horizontal shear between the Gulf Stream and the continental shelf forming a cyclonic gyre. The gyre flows to the south on the continental shelf and to the north in the Gulf Stream, beyond the shelf break. Calculations suggest that the alongshore pressure gradient (surface slope) will decrease to the south with a decrease in the width of the shelf (Bush and Kapferman, 1980; Beardsley and Boicourt, 1981). The southward geostrophic flow on the shelf yields velocities of 30 to 45 cm/s and net water excursions of 40 to 70 km (Beardsley and Butman, 1974).

Temperature-salinity diagrams can provide further support of seasonal circulation patterns. The water column on the shelf of the Mid-Atlantic Bight is stratified throughout much of the year (Boicourt, 1973; Hunt et al., 1977). During November and December, stratification breaks down as a result of cooling temperatures and turbulent mixing from winter storms. The water column remains stratified annually due to fresh water input from the Chesapeake Bay, and below 30 m due to warm high salinity water at the shelf break. However, as the width of the shelf narrows to the south, towards Oregon Inlet, stratified inner shelf water mixes with homogeneous mid-shelf waters (Boicourt, 1973). To the south of Cape Hatteras, frontal eddies occur in stratified waters as “tongues” of colder, less saline water on the shoreward side of the Gulf Stream (Glenn and Ebbesmeyer, 1994). Drifter observations show that Gulf Stream frontal eddies can propagate north of Cape Hatteras on the outer continental shelf, contributing to stratification of the water column.

2.2.4 Waves and Wave-Generated Currents

Since 1980, wave measurements have been collected approximately 6 km offshore of the USACE FRF in Duck, NC in 18 m water depth. An annual average wave height of 1.0 m and period of 8.3 sec was estimated from a ten-year record (1980-1990) (Leffler et al., 1992). At this location, wave heights exceeded 3 m approximately 1.4% of the time and were classified as “severe storms”. During the Halloween storm of 1991, the largest and longest period waves (6 m and 22 s) occurred after local winds had weakened and turned to the northwest (offshore) (Wright et al., 1994). Birkemeier et al. (1981) reported that wave heights and periods frequently exceed 4 m and 10 sec during extra-tropical storms from October to February. Wave directions were seasonally distributed, typically approaching from the north in the fall and winter and from the south in summer. Storm waves approach from the north approximately 70% of the time (Leffler et al., 1992).

Infragravity frequency (0.03-0.003 Hz) motions are correlated with wave groups and play an important secondary role in sediment transport on the shoreface off of Duck, NC (Wright et al., 1994). During calm periods, infragravity flows are weak (5 cm/s), but can increase to an amplitude of 20 cm/s during northeast storm events. Although the total infragravity signal is comprised of group-forced long waves, edge waves, and leaky-mode standing waves, at least 50% of the infragravity signal on the inner shelf of North Carolina originates from the surf zone (Okihiro et al., 1991; Guza, 1992).

2.2.5 Nearshore Sediment Transport

Between Cape Henry and Cape Hatteras, Inman and Dolan (1989) state that longshore transport typically moves sediment from north to south, although there is spatial and temporal variation within this pattern (Figure 2-26). Extra-tropical storms are responsible for the most significant coastal erosion (Madsen et al., 1993; Wright and Madsen, 1994). Swell and storm conditions produce surface gravity waves that create sediment agitating bed stress (Wright, 1993). Near bed wave orbital velocities of up to 100 cm/s have been measured during a northeast storm (Wright et al., 1991). During an extreme storm event, wave conditions, near-bottom orbital velocities, and suspended sediment concentrations measured in 13 m water depth indicated movable flat bed conditions and significant sediment transport potential (Madsen et al., 1993). Fluid-sediment interactions during the storm were sufficient to wash out ripples on the bed. However, near-bottom mean flows play the primary role in transporting sand across isobaths on the shoreface of the Mid-Atlantic Bight, distinguishing it from high-energy shoreface environments where the persistent swell creates a dominant oscillatory component (Wright et al., 1991).

Sediment transport processes on the shelf of the Mid-Atlantic Bight are storm dominated (Wright, 1993). Evidence suggests the net direction of sediment transport on the shelf is south between Long Island and Cape Hatteras (Swift et al., 1972). However, transverse shelf valleys partition the floor of the Mid-Atlantic Bight acting as sand traps and preventing sand from moving any appreciable distance (Hunt et al., 1977). Observations have shown a significant portion of the surficial sand sheet of the northern portion of the North Carolina shelf has been delivered to the shelf edge of Diamond Shoals, is mixed with silt settling out of the Gulf Stream, and subsequently is deposited in the Hatteras Canyon (Hunt et al., 1977). The valleys and canyons act as sinks to shelf sediments but sources to the offshore. A study by Horn et al. (1971) suggested that sediment of the abyssal plain west of the Mid-Atlantic Ridge were derived from the Hudson and Hatteras canyon systems.

2.3 BIOLOGY

2.3.1 Benthic Environment

The following subsections provide summaries of the existing literature concerning the benthic environment, including infauna (Section 2.3.1.1) and epifauna and demersal fishes (Section 2.3.1.2), in and around the four sand resource areas. This information, along with the assessment of ecological conditions from the biological field surveys (Section 6.0), provides the framework for the evaluation of potential effects from dredging on these organisms (Section 7.5).

2.3.1.1 Infauna

Infaunal organisms collected during previous investigations of inner shelf waters offshore North Carolina predominantly consist of members of the major invertebrate groups that commonly inhabit sand bottom marine ecosystems, including crustaceans, echinoderms,

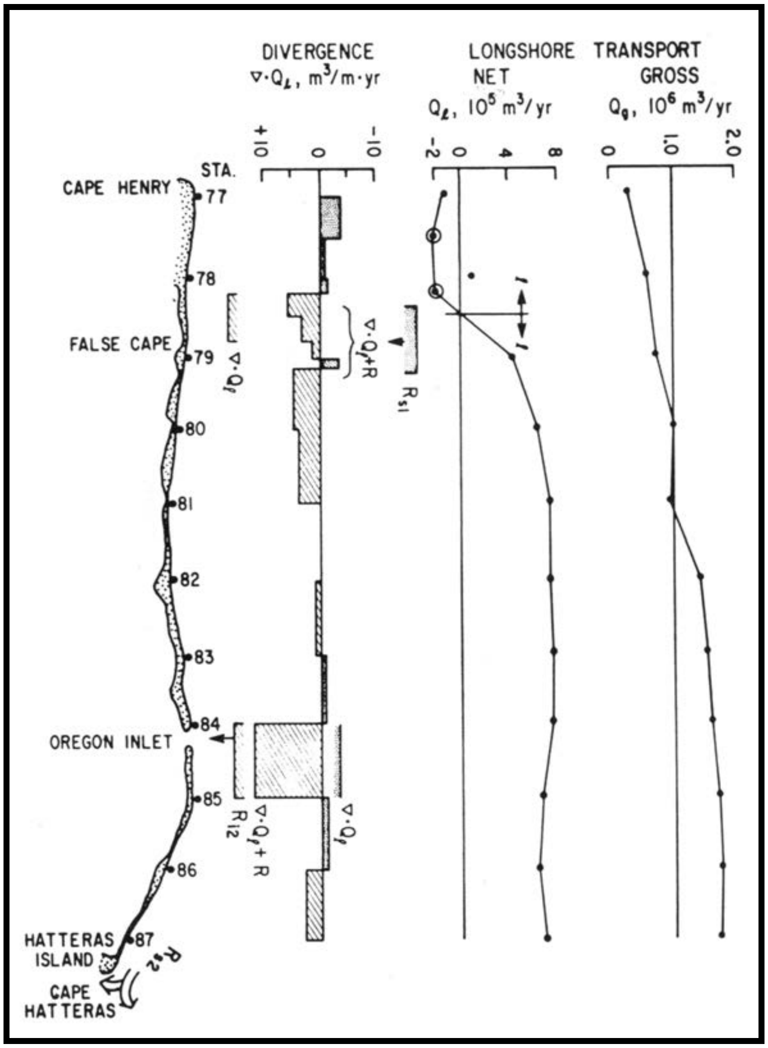

Figure 2-26. Variations in sand transport potential between Cape Henry, VA and Cape Hatteras, NC (from Inman and Dolan, 1989).

mollusks, and polychaetous annelids. Infaunal assemblages that inhabit shelf waters offshore North Carolina resemble assemblages common to much of the Middle Atlantic Bight (Wigley and Theroux, 1981). Generally, inner shelf infaunal assemblages are numerically dominated by polychaetes in terms of abundance and numerically dominant taxa (Day et al., 1971; Weston, 1988). Other conspicuous members of the coastal North Carolina infaunal community include amphipod crustaceans and bivalve mollusks. Infaunal taxa that inhabit inner shelf sand bottoms offshore North Carolina comprise assemblages that exhibit spatial and seasonal variability (Day et al., 1971; Boesch, 1972; Wigley and Theroux, 1981; Weston, 1988; MMS, 1989).

The distribution and abundance of infaunal populations that comprise North Carolina inner shelf communities are affected by abiotic environmental parameters. Spatially variable factors such as hydrology, water depth, and sediment type influence benthic assemblages and the extent of numerical dominance of those assemblages by various infaunal populations.

Cerame-Vivas and Gray (1966) found that north of Cape Hatteras, inner- and mid-shelf benthic invertebrate assemblages are representative of the Virginian Province, while Carolinian Province fauna predominate south of the Cape, with relatively few taxa ranging into both areas.

The authors further determined that the OCS offshore North Carolina was dominated by Caribbean Province epifauna. However, Day et al. (1971) found that these faunal zone delineations might not be as distinct when examining infaunal distribution. The area apparently does represent at least a marginal transition zone for some infaunal taxa. Gardiner (1976) reported that for motile polychaetes, the area offshore North Carolina represents the northern distributional limit for about 12% of species and the southern distributional limit for about 14% of species occurring in waters offshore North Carolina.

In a report based on 667 quantitative samples of benthic fauna collected from the Middle Atlantic Bight between 1956 and 1965, Wigley and Theroux (1981) summarized the relationship between water depth and infaunal abundance. The southern extent of the overall study region extended to Cape Hatteras and greatest infaunal densities in the region occurred at relatively shallow depths. With increasing water depth, abundance of each of the major taxonomic groups (e.g., bivalves) generally decreased, although not uniformly across taxonomic groups. For purposes of analysis, the Middle Atlantic Bight region was divided into subareas. In the Chesapeake Bight subarea in water depths less than 24 m, bivalves were numerically dominant (1,136 individuals/m^2), followed by amphipod crustaceans (198/m^2) and annelids (183/m^2). The relative paucity of annelids in the Wigley and Theroux (1981) study contrasts with other studies that found polychaetes to be the most conspicuous components of infaunal assemblages in inner shelf waters offshore North Carolina (Day et al., 1971; Weston, 1988).

Day et al. (1971) determined the distribution of infauna along a depth gradient from the beach zone to the edge of the continental shelf off Cape Lookout, NC. Infauna was sampled five times during a 1-year period using benthic grabs. Based on faunal composition, four subtidal zones were delineated at increasing depth intervals. The turbulent zone included the inner shelf between 3- and 20-m depths, and corresponds with the location of the sand resource areas that are the subject of the present study. The most abundant infaunal species within the turbulent zone included the amphipod *Protohaustorius* sp., the archiannelid *Polygordius*, and the polychaetes *Bhawania* (=*Palaenotus*) *heteroseta*, *Goniadides carolinae*, *Macroclymene zonalis*, and *Magelona papillicornis*. The most common taxa of the turbulent zone were best represented at the 20-m depth station (Day et al., 1971).

The effect of water depth on benthic assemblages may in some cases be defined more precisely as an effect of depth-related environmental factors, including parameters that vary with increasing depth, such as current regime, dissolved oxygen, sedimentary regime, and temperature. Surficial sediments tend to be well sorted at shallow depths, due primarily to the mixing of shelf waters by storms. In broad terms, inner shelf waters are less depositional in nature than outer shelf or slope waters due to a dynamic current regime, but shallow areas near an area affected by estuarine outflow may experience episodic deposition of fine materials, and thereby influence benthic community structure. Although existing descriptions of depth-related differences in benthic assemblages have encompassed geographically broad areas (Day et al., 1971; Wigley and Theroux, 1981), local variability in bathymetric relief can result in habitat heterogeneity within an area of relatively minor depth differences. Trough features, especially those that are bathymetrically abrupt, can dissipate current flow along the substratum surface. Reduction of current flow can result in deposition of fine materials, including organic material. The presence of fine sediments and organics in bathymetric depressions can support benthic assemblages that are distinct from nearby areas without depressions (Boesch, 1972).

Certain infaunal populations are distributed in approximately equal numbers from shallow waters to the edge of the shelf (e.g., the polychaete *Nephtys picta*), while others occur mostly on the inner shelf (e.g., the polychaete *M. papillicornis*) or mid to outer shelf (e.g., the polychaete *Scalibregma inflatum*). Although there is a negative correlation between infaunal abundance and water depth, it is unclear whether such faunal distributions are affected mostly by absolute water depth, or whether factors such as hydrology, sedimentary regime, and seasonality override any effects of sediment particle size and type on infaunal assemblages.

Previous sampling efforts in Atlantic shelf waters have demonstrated the importance of sediment type in determining infaunal population densities. Coarse-grained sediments generally support greatest numbers of infauna, while fine-grained sediments support the least (Wigley and Theroux, 1981; MMS, 1989). Wigley and Theroux (1981) summarized the relationship between sediment type and infaunal abundance of the Middle Atlantic Bight. Amphipods are found in all sedimentary habitats, though densities are greatest in sand-gravel and sand habitats. Generally, bivalve densities are greatest in sand-shell sediments and decrease with increasing sediment particle size, although shell fragment habitats can support moderately high bivalve numbers. Gravel bottoms support the lowest densities of bivalves. Polychaetes occur in all sediment types, although greatest abundances are found in sand and gravel bottoms and least in silt-clay habitats (Wigley and Theroux, 1981).

Sediment particle size also has a qualitative effect on the species composition of benthic assemblages (Sanders, 1958; Young and Rhoads, 1971; Pearce et al., 1981; Barry A. Vittor & Associates, Inc., 1985; Weston, 1988; Chang et al., 1992). Although many infaunal species inhabit a variety of sediment types (e.g., the polychaete *S. bombyx*), many infaunal taxa tend to predominate in specific sedimentary habitats.

In an investigation conducted offshore Cape Hatteras, Weston (1988) confirmed the findings of other studies in the Middle Atlantic Bight that found sedimentary regime a reliable predictor of the distribution of certain infaunal taxa. During the Weston (1988) study, grab samples were collected during four quarterly cruises at water depths ranging from 23 to 54 m. Cluster analysis was performed on the taxonomic data to delineate groups of stations that were similar with respect to infaunal composition. Four groups of stations (Groups 1 through 4) were delineated based on sample composition. Stations characterized by fine sand and relatively greater amounts of silt and clay (Group 1) were numerically dominated by the amphipod *Ampelisca verrilli* and the polychaetes *Aglaophamus verrilli*, *Aricidea catherinae*, *Goniada littorea*, *Mediomastus californiensis*, and *Paraprionospio pinnata*. The medium- to fine-grained sand community (Group 2) was numerically dominated by the archiannelid *Polygordius* and also supported high densities of the polychaetes *Glycera oxycephala* and *Magelona* cf. *pettiboneae*. Other investigations have found that great abundances of *Polygordius* commonly occur in inner shelf sand bottoms (Rabalais and Boesch, 1987), although *Polygordius* also has been observed to be common in coarser sediments, including shell hash (Barry A. Vittor & Associates, Inc., 1985). The coarsest sediments in the Weston (1988) study were characterized by interstitial taxa occurring in relatively low numbers. Coarse sand and gravel areas (Group 3) offshore Cape Hatteras commonly yielded polychaetes such as *Hemipodus roseus*, *Hesionura elongata*, and *Pionosyllis gesae*, and surf clam (*Spisula solidissima similis*). The fourth group of stations was characterized by well-sorted, fine sand (Group 4) that was numerically dominated by the burrowing amphipods *Bathyporeia parkeri*, *Protohaustorius* cf. *deichmannae*, and *Rhepoxynius epistomus*. Overall, the percentage of fine sand and combined percentage of silt and clay were the parameters of greatest value in differentiating infaunal assemblages offshore Cape Hatteras (Weston, 1988).

Infaunal assemblages are composed of taxa that are adapted to particular sedimentary habitats through differences in behavioral, morphological, physiological, and reproductive characteristics. Feeding is one of the behavioral aspects most closely related to the sedimentary habitat (Sanders, 1958; Rhoads, 1974). In general, coarse sediments in high water current habitats, where organic particles are maintained in suspension in the water column, favor the occurrence of suspension-feeding taxa that strain food particles from the water column. Coarse sediments also facilitate the feeding of carnivorous taxa that consume organisms occupying interstitial habitats (Fauchald and Jumars, 1979). At the other extreme, habitats with fine-textured sediments and little or no current are characterized by the deposition and accumulation of organic material, with these habitats supporting surface and subsurface deposit feeding taxa. In between these habitat extremes are a variety of habitat types that differ with respect to various combinations of sedimentary regime, depth, local bathymetry, and hydrological factors. These different habitats tend to support particular infaunal assemblages that tend to vary over time.

2.3.1.2 Epifauna and Demersal Fishes

The benthic ecosystem of inner continental shelf waters offshore North Carolina is recognized as a zone of convergence of distinct faunal provinces. Based on the contents of qualitative dredge samples, Cerame-Vivas and Gray (1966) established that the inner continental shelf offshore North Carolina is divided into two faunal zones, with each of these characterized by epibenthic invertebrate assemblages corresponding to distinct biogeographic provinces. North of Cape Hatteras, inner- and mid-shelf sand bottom, epifaunal assemblages are representative of the Virginian Province, while Carolinian Province fauna predominate south of the Cape, with relatively few taxa ranging into both areas. Williams (1984) found that Cape Lookout may be a greater barrier to the northern extension of decapods than Cape Hatteras, and concluded that the region encompassing the two Capes represents a major barrier to about 50% of southern decapod fauna that occur along the U.S. Atlantic coast. The demarcation of biogeographic provinces in the area of Cape Hatteras largely is a result of interaction between various ocean currents that determine the latitudinal extent of relatively cooler or warmer water temperatures, creating an ecological barrier for members of the respective province assemblages.

Many numerically dominant epifauna that inhabit inner shelf waters may be described more precisely as epibenthic, especially gastropods and decapods, although these taxa routinely are collected along with infauna using grab samplers. Certain epifaunal taxa, such as lady crab (*Ovalipes ocellatus*), commonly burrow deeply into sediments; adaptive behaviors of this type can complicate efforts to categorize such taxa into a specific, lifestyle-based, invertebrate group. Many bivalves are effectively sampled using either a trawl or grab method. Given this dilemma of ecological classification, however, the taxa discussed below commonly are collected in trawl samplers and, for the sake of comparison and consistency with previous investigations, herein are considered epifauna.

Other than certain asteroid echinoderms, most epifaunal taxa sampled by Cerame-Vivas and Gray (1966) north of Cape Hatteras also were found south of the Cape. Decapod crustaceans were especially prevalent in qualitative dredge samples during the study. Those decapods that were found along the entirety of the North Carolina inner shelf included Atlantic rock crab *Cancer irroratus*, blue crab *Callinectes sapidus*, lady crab *O. ocellatus*, hermit crab *Pagurus longicarpus*, rock shrimp *Sicyonia breviostris*, and sevenspine bay shrimp *Crangon septemspinosa*. Common inner shelf echinoderms that were found during the study included the asteroids *Asterias forbesi*, *Astropecten americanus*, and *Luidia clathrata*, and the sand dollar *Mellita quinquiesperforata*. Of the gastropods, *Natica pusilla* was the only species identified as characteristic of the Virginian Province (i.e., primarily occurring north of Cape Hatteras) (Cerame-Vivas and Gray, 1966). The most common epifauna collected by Day et al. (1971) in inner shelf waters offshore Cape Lookout included the sand dollar *M. quinquiesperforata*, hermit crabs (*Pagurus* spp.), and olive shells (*Olivella* spp.). Squids (*Loligo* spp.) commonly are collected in trawl hauls in the Middle Atlantic Bight.

Certain epifauna are associated with particular sedimentary habitats (Wigley and Theroux, 1981). Gastropod densities generally are greatest in areas of coarse sand and gravel. Coarse sediments are more suitable for locomotion by broad-footed benthic mollusks than are areas of fine sediments, which are relatively unstable. Decapods generally are found in areas of gravel and shell, although species such as *C. septemspinosa* tend to occur in areas of sand, while the crab *C. irroratus* inhabits a variety of sediment types. The sand dollars *Echinarachnius parma* and *M. quinquiesperforata* most commonly are associated with sand habitats, while brittle stars are most common in silty sand, probably due to greater efficiency of burrowing in finer sediments. Sea stars tend to be distributed across a range of sediments, from shelly sand to silt habitats (Wigley and Theroux, 1981).

Demersal fishes inhabiting shelf waters offshore of northern North Carolina include a mixture of species with differing zoogeographic affinities, such as warm temperate, temperate, and boreal (Colvocoresses and Musick, 1984; Ross, 1985). This results in temporally dynamic assemblages with large seasonal changes in species presence and abundance. Depth and temperature are the most important large-scale environmental factors influencing distributions and abundances of demersal fishes in this region (Colvocoresses and Musick, 1984). In response to seasonally changing temperature, some species move north or south along the shelf, whereas others move onshore and offshore. The most abundant demersal species from the area north of Cape Hatteras include Atlantic croaker (*Micropogonias undulatus*), spot (*Leiostomus xanthurus*), weakfish (*Cynoscion regalis*), summer flounder (*Paralichthys dentatus*), and spiny dogfish (*Squalus acanthius*) (Ross, 1985). A large geographical area extending from Cape Hatteras, NC to Nova Scotia is considered wintering grounds for spiny dogfish and summer flounder (USACE, 2000). Other less abundant but frequently occurring species are Atlantic sturgeon (*Acipenser oxyrhynchus*), silver hake (*Merluccius bilinearis*), black sea bass (*Centropristis striata*), and scup (*Stenotomus chrysops*). Many species mentioned above are present and targeted by the winter trawl fishery in outer shelf waters from October to early April (Ross, 1985; North Carolina Division of Marine Fisheries, 1990).

Atlantic sturgeon is an anadromous species that spends a portion of its life history in North Carolina shelf waters, ascending rivers such as the Pamlico, Neuse, and Cape Fear to spawn during spring (Ross et al., 1988). Following several years in freshwater or estuarine habitats, young Atlantic sturgeons move into coastal and shelf waters to feed and grow until they reach maturity. Shortnose sturgeon (*Acipenser brevirostris*) is an endangered anadromous species but only occurs in inland waters throughout its life cycle and should not be affected by activities at the sand resource areas. Records of shortnose sturgeon in shelf or coastal waters are likely mistaken identifications of *A. oxyrhynchus* (Ross et al., 1988).

Much of the diet of Middle Atlantic fishes consists of other fishes; however, the diet of many of the most common demersal fishes consists of epibenthic and infaunal invertebrates (Grosslein, 1976). The affinity of certain demersal fishes for particular sediment types often is related to the types of prey items supported by those sediments (Rogers, 1977). Species such as butterfish, flounders, skates (*Raja* spp.), and spot are predominantly bottom feeders that consume infaunal and epibenthic crustaceans and polychaetes. Amphipods are known to be important in the diets of some demersal fishes, including Atlantic croaker, hakes, scup, skates, and windowpane. Certain demersal foragers therefore may be attracted to areas of sands, where crustaceans and polychaetes are most abundant (Wigley and Theroux, 1981).

2.3.2 Pelagic Environment

The pelagic environment supports several living components of the nearshore shelf ecosystem. These include zooplankton, ichthyoplankton, and fishes. The available literature for the Middle Atlantic Bight region supplied most of the information presented in this section. These studies included general information relevant to the North Carolina shelf as it is embedded within the larger region. As with other biotic components, the pelagic environment of this region is transitional due primarily to the confluence of several different water masses in the Cape Hatteras area.

2.3.2.1 Zooplankton

Zooplankton form an essential link in the marine food web between the primary producers (phytoplankton and bacteria) and larger marine species such as fishes, birds, and marine mammals. They are relatively weak swimmers that drift with the currents. Zooplankton transport organic matter through the water column by their vertical migration and by the production of organically rich fecal pellets that sink to the seafloor.

Zooplankton can be functionally divided into holoplankton and meroplankton. Holoplankton spend their entire lives in the water column, whereas meroplankton occur as plankton only during certain stages (generally larval stages) of their life cycle. Many important commercial and recreational fish species have planktonic eggs and larvae. Holoplankton and non-fish meroplankton are discussed together in this zooplantkon section. Fish eggs and larvae are discussed separately in the ichthyoplankton section, which occurs after this section.

Major constituents of the zooplankton include gelatinous zooplankton, copepods, and chaetognaths. Other groups include amphipods, euphausiids, heteropods, cladocerans, polychaetes, and pteropods. In the Middle Atlantic Bight, zooplankton assemblages were studied by Sherman et al. (1983, 1984) and Kane (1997). These studies were based on collections in the Middle Atlantic Bight region conducted by the NMFS (e.g., Smith, 1988; Smith and Morse, 1988) primarily through the Marine Monitoring, Assessment and Prediction Program (MARMAP). Under this program, zooplankton samples have been collected at cross-shelf stations throughout the northeastern continental shelf from the Gulf of Maine to Cape Hatteras since the 1970's. The Middle Atlantic Bight extending from Cape Cod to Cape Hatteras was a regional subarea within the MARMAP sampling scheme. Independently of MARMAP, Grant (1988, 1991) sampled zooplankton in the Middle Atlantic Bight offshore Virginia.

Zooplankton species composition in the Middle Atlantic Bight appears to be persistent over time. Comparisons of zooplankon samples collected over a wide spatial grid annually for 5 years with older studies revealed that species composition and biomass in the northeastern Atlantic (including the Middle Atlantic Bight) have not changed appreciably in 70 years (Sherman et al., 1983, 1984). The seasonal pattern in zooplankton abundance and biomass is an annual low in winter to an autumn high (Sherman et al., 1983, 1984). This pattern was persistent within the Middle Atlantic Bight over the 5-year period (Sherman et al., 1983). Observed seasonal patterns were mostly driven by numerically dominant copepods (e.g., Kane, 1997). Twelve copepod taxa (*Calanus finmarchicus*, *Pseudocalanus* sp., *Centropages typicus*, *Metridia lucens*, *Temora longicornis*, *Centropages hamatus*, *Acartia tonsa*, *Acartia* spp., *Oithona* spp., *Calanus* spp., and *Paracalanus parvus)* represented 85% of the zooplankton abundance for the region (Sherman et al., 1983). Of these taxa, *C. finmarchicus*, *P. minutus*, and *C. typicus* accounted for 75% of the zooplankton abundance.

Patterns of zooplankton abundance vary within and among the subregions of the northeastern Atlantic shelf. In the southern Middle Atlantic Bight, *C. finmarchicus* abundance is lower, and is replaced by *P. minutus* and *C. typicus* in late winter and early spring. From summer to fall the zooplankton abundance increased, mostly due to abundant cladocerans and *C. typicus* (Sherman et al., 1983). Members of the genus *Centropages*, other than *C. typicus*, were distributed variously based on water depth, temperature, and season (Grant, 1988). Two species restricted to inshore areas (<50 m water depths) were *C. hamatus* and *C. velificatus*. The abundance of *C. hamatus* peaked during winter and spring, whereas *C. velificatus* was most abundant in summer and fall.

2.3.2.2 Ichthyoplankton

The ichthyoplankton assemblage found in the Middle Atlantic Bight including northern North Carolina generally corresponds with the existing adult fish assemblage (Able and Fahay, 1998). This adult fish assemblage consists of some resident species, but most are migrants from northern or southern waters. Northern species migrate south during winter months and southern species migrate north in the summer months. This pattern is seen in the occurrence of larval fishes in the Middle Atlantic Bight. Many of the transient species spawn while moving through Middle Atlantic Bight waters, thus contributing to the abundance and diversity of the local ichthyoplankton assemblages. Some larval taxa found in the Middle Atlantic Bight are spawned in more southerly waters of the South Atlantic Bight and transported northward by the Gulf Stream (Cowen et al., 1993). Because the spawning times of adults can be inferred from egg and larval occurrences, this information is given to augment information on temporal patterns of ichthyoplankton occurrence. Table 2-2 gives the spawning times and locations of important species from the region.

Long-term investigations of ichthyoplankton in the Middle Atlantic Bight region have been conducted by the NMFS (e.g., Smith, 1988; Smith and Morse, 1988) primarily through MARMAP. Summaries exist for various portions of the program (e.g., Sherman et al., 1984; Smith, 1988; Smith and Morse, 1988; Doyle et al., 1993). MARMAP collections from the central Middle Atlantic Bight were recently summarized by Able and Fahay (1998). Grothues and Cowen (1999) recently studied the relationship between larval fish assemblages and water masses in the vicinity of Cape Hatteras where the Middle Atlantic Bight and South Atlantic Bight meet. This study included cross-shelf transects near the four North Carolina sand resource areas.

More than 200 taxa of fish eggs and larvae were recorded from Middle Atlantic Bight waters by MARMAP (Smith and Morse, 1988). Fifty taxa represented most of the fish larvae collected from the entire northeastern Atlantic shelf (Doyle et al., 1993). Based on occurrence of larvae, Doyle et al. (1993) recognized a general Middle Atlantic Bight assemblage; however, when abundance was considered, spatial and seasonal sub-components appeared. For example, a southern Middle Atlantic Bight sub-component consisted of anchovies (Engraulidae), searobins (Triglidae), black sea bass (*Centropristis striata*), gobies (Gobiidae), and tonguefishes (*Symphurus* spp.).

A persistent seasonal cycle was documented for eggs and larvae in the Middle Atlantic Bight that reflects adults spawning times (Smith and Morse, 1988). Eggs occur in relatively low numbers during late winter, but by mid-April they were abundant and peak levels were reached in June. Numbers of larvae exhibited a similar seasonal pattern with a peak in summer. Each season’s samples were numerically dominated by different larval taxa (Sherman et al., 1984). In winter, sand lances exceeded all taxa in abundance representing over 90% of the numbers collected. In spring, the rank order of abundance was a lanternfish (*Benthosema glaciale*), Atlantic mackerel (*Scomber scombrus*), sand lance, windowpane, butterfish, and yellowtail flounder. In summer, smallmouth flounder, Gulf Stream flounder, anchovies, bluefish (*Pomatomus saltatrix*), butterfish, and searobins (*Prionotus* spp.) were numerically dominant. By fall, searobins, Atlantic croaker (*Micropogonias undulatus*), hakes (*Urophycis* sp.), Gulf

Table 2-2. Summary of spawning times and location of fishes in the central part of the Middle Atlantic Bight (Adapted from: Able and Fahay, 1998).

Species	Spawning Time	Spawning Location	Egg Type
Carcharhinidae			
Mustelus canis	Sp	Estuary/MAB	Live
Anguillidae			
Anguilla rostrata	Sp	SS	Unknown
Clupeidae			
Alosa aestivalis	Sp	FW	Pelagic
Brevoortia tyrannus	Fa, Sp	MAB/SAB	Pelagic
Clupea harengus	Sp	MAB	Demersal
Engraulidae			
Anchoa hepsetus	Su	MAB	Pelagic
A. mitchilli	Su	Estuary/MAB	Pelagic
Synodontidae			
Synodus foetens	Unknown	SAB	Unknown
Gadidae			
Pollachius virens	Fa-Wi	MAB	Pelagic
Phycidae			
Urophycis chuss	Su	MAB	Pelagic
U. regia	Sp-Fa	MAB	Pelagic
U. tenuis	Sp	MAB (Slope)	Pelagic
Ophidiidae			
Ophidion marginatum	Su-Fa	MAB	Pelagic
Syngnathidae			
Hippocampus erectus	Sp-Su	Estuary/MAB	Live
Triglidae			
Prionotus carolinus	Su-Fa	MAB (Estuary?)	Pelagic
P. evolans	Su-Fa	MAB (Estuary?)	Pelagic
Serranidae			
Centropristis striata	Sp-Fa	MAB	Pelagic
Pomatomidae			
Pomatomus saltatrix	Sp-Su	SAB/MAB	Pelagic
Carangidae			
Caranx hippos	Unknown	SAB	Pelagic
Lutjanidae			
Lutjanus griseus	Su	SAB	Pelagic
Sciaenidae			
Bairdiella chrysoura	Su	Unknown	Pelagic
Cynoscion regalis	Sp-Su	Estuary/MAB	Pelagic
Leiostomus xanthurus	Wi	MAB	Pelagic
Menticirrhus saxatilis	Su	MAB	Pelagic
Micropogonias undulatus	Su-Fa	MAB	Pelagic
Pogonias cromis	Su	MAB	Pelagic
Chaetodontidae			
Chaetodon ocellatus	Unknown	SAB	Pelagic
Mugilidae			
Mugil cephalus	Wi	SAB	Pelagic
M. curema	Sp	SAB	Pelagic
Sphyraenidae			
Sphyraena borealis	Sp	SAB	Pelagic
Labridae			
Tautoga onitis	Sp-Fa	Estuary/MAB	Pelagic
Tautogolabrus adspersus	Sp-Fa	MAB	Pelagic
Pholidae			
Pholis gunnellus	Wi	Estuary/MAB	Demersal
Uranoscopidae			
Astroscopus guttatus	Su	Estuary/MAB	Unknown
Stromateidae			
Peprilus triacanthus	Sp-Su	Estuary/MAB	Pelagic
Scophthalmidae			
Scophthalmus aquosus	Sp,Fa	Estuary/MAB	Pelagic
Paralichthyidae			
Etropus microstomus	Sp-Fa	MAB	Pelagic
Paralichthys dentatus	Fa-Wi	MAB	Pelagic
Pleuronectidae			
Pseudopleuronectes americanus	Wi	Estuary/MAB	Demersal

Spawning Time
Fa = Fall.
Sp = Spring.
Su = Summer.
Wi = Winter.

Spawning Location
FW = Fresh water.
MAB = Middle Atlantic Bight.
SAB = South Atlantic Bight.
SS = Sargasso Sea.

stream flounder, smallmouth flounder, and lefteye flounders (Bothidae) numerically dominated the collections. Able and Fahay (1998) summarized the species composition and monthly occurrence of larval fishes from MARMAP collections made in the central Middle Atlantic Bight which focused primarily on the New Jersey shelf but are relevant to the North Carolina sand resource areas (Table 2-3).

Several species mentioned above that are present as larvae and juveniles in the Middle Atlantic Bight actually were spawned in more southerly waters. Grothues and Cowen (1999) found that larvae of species spawned in waters south of Cape Hatteras often appear offshore in the Middle Atlantic Bight, transported to the area by the Gulf Stream. Many of these taxa, especially those of southern origin, do not survive in the Middle Atlantic Bight due to low water temperatures or other stressors. Two species spawned in southerly waters that do survive are bluefish and butterfish. Larvae and juveniles of these species enter offshore waters of the Middle Atlantic Bight and make their way into inshore waters where they spend their first year of life (Cowen et al., 1993; Rotunno and Cowen, 1997). These species appear to have adapted their cross-shelf migration to the complex circulation of the Middle Atlantic Bight. Species that are not adapted to early life in the Middle Atlantic Bight include razorfish (*Xyrichthys*) and some flatfishes (*Bothus* spp. and *Syacium* spp.).

Grothues and Cowan (1999) collected larvae from different water masses north and south of Cape Hatteras and found distinct assemblages associated with each water mass. Assemblages identified that were pertinent to the North Carolina sand resource areas were a Middle Atlantic Bight assemblage and a transitional assemblage consisting of species derived from both Middle Atlantic Bight and South Atlantic Bight regions. The Middle Atlantic Bight assemblage included larval yellowtail flounder (*Limanda ferruginea*), goosefish (*Lophius americanus*), and Atlantic mackerel. The transitional assemblage consisted of larval searobins, *Etropus crossotus*, herrings, anchovies, butterfish, gulfstream flounder, and lizardfishes. These assemblages were thought to persist through a combination of physical processes (currents and fronts) and larval behavior (Grothues and Cowen, 1999).

2.3.2.3 Squids

Squids (cephalopods) display patchy distributions and periodic vertical and horizontal migrations. Water quality, currents, and temperature principally control the occurrence of squids, while food and population density affect movements within suitable water masses.

Two squid species are common in North Carolina shelf waters: the longfin squid (*Loligo pealei*) and the shortfin squid (*Illex illecebrosus*) (Lange and Sissenwine, 1980). These are the squids most likely to occur in or near the four sand resource areas. The longfin squid, a member of the family Loliginidae, occurs primarily in shelf and shelf edge waters from Newfoundland to the Gulf of Venezuela. Its distribution, determined by fishery independent sampling, is influenced by water temperature, depth, and time of day (Brodziak and Hendrickson, 1999). A general seasonal migratory pattern has been observed for the Middle Atlantic Bight population. Adults move offshore in fall and remain there until April, at which time adults and young migrate back into shelf waters for the summer (Lange and Sissenwine, 1980). Spawning reportedly occurs year-round with major peaks in spring (April and May) and fall (August and September). Longfin squid grow rapidly and live about one year (Lange and Sissenwine, 1980; Brodziak and Macy, 1996). This species represents an important fishery in the Middle Atlantic Bight with annual landings averaging 18,200 MT (Cadrin, 1998). Commercial fishing for longfin squid takes place from Cape Hatteras to Georges Bank. It is

Table 2-3. Ranking of the most abundant larval fishes collected in continental shelf waters in the central part of the Middle Atlantic Bight during the Marine Monitoring, Assessment and Prediction Program (MARMAP) surveys from 1977 to 1987 (Adapted from: Able and Fahay, 1998).

Taxon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ammodytes spp.	1	1	1	1	2	--	--	--	--	--	--	4
Gadus morhua	2	3	2	3	7	--	--	--	--	--	--	7
Paralichthys dentatus	3	2	9	--	--	--	--	--	--	5	2	1
Brevoortia tyrannus	4	--	--	--	--	--	--	--	--	--	5	5
Merluccius bilinearis	5	9	--	--	--	7	9	9	--	6	4	2
Maurolicus muelleri	6	--	--	--	--	--	--	--	--	--	--	8
Leiostomus xanthurus	7	--	--	--	--	--	--	--	--	--	--	--
Pollachius virens	8	4	7	--	--	--	--	--	--	--	--	--
Gobiidae	9	--	--	--	--	--	--	--	--	--	8	--
Clupea harengus	10	--	--	--	--	--	--	--	--	--	--	--
Micropogonias undulatus	11	--	--	--	--	--	--	--	--	--	--	--
Pholis gunnellus	--	5	4	11	--	--	--	--	--	--	--	--
Myoxocephalus octodecemspinosus	--	6	3	10	--	--	--	--	--	--	--	--
Paralepididae	--	7	--	--	--	--	--	--	--	--	--	--
Anguilla rostrata	--	8	--	--	--	--	--	--	--	--	--	--
Notolepis rissoi	--	10	10	--	--	--	--	--	--	--	--	--
Pseudopleuronectes americanus	--	--	5	5	--	--	--	--	--	--	--	--
Myoxocephalus aenaeus	--	--	6	9	--	--	--	--	--	--	--	--
Cottidae	--	--	8	7	--	--	--	--	--	--	--	--
Benthosema glaciale	--	--	--	2	9	--	--	--	--	--	--	--
Limanda ferruginea	--	--	--	4	1	1	10	--	--	--	--	--
Liparis spp.	--	--	--	6	5	--	--	--	--	--	--	--
Melanogrammus aeglefinus	--	--	--	8	10	--	--	--	--	--	--	--
Scomber scombrus	--	--	--	--	3	3	--	--	--	--	--	--
Enchelyopus cimbrius	--	--	--	--	4	2	--	--	--	--	10	--
Scophthalmus aquosus	--	--	--	--	6	6	11	--	--	3	3	3
Glyptocephalus cynoglossus	--	--	--	--	8	5	--	--	--	--	--	--
Lophius americanus	--	--	--	--	--	4	7	--	--	--	--	--
Tautogolabrus adspersus	--	--	--	--	--	8	3	7	--	--	--	--
Hippoglossina oblonga	--	--	--	--	--	9	1	2	4	8	--	--
Urophycis chuss	--	--	--	--	--	10	4	--	--	--	--	--
Peprilus triacanthus	--	--	--	--	--	--	2	1	8	--	--	--
Pomatomus saltatrix	--	--	--	--	--	--	5	6	--	--	--	--
Engraulidae	--	--	--	--	--	--	6	8	10	--	--	--
Citharichthys arctifrons	--	--	--	--	--	--	8	4	2	2	6	--
Urophycis spp.	--	--	--	--	--	--	--	3	1	--	--	--
Etropus microstomus	--	--	--	--	--	--	--	5	3	7	--	--
Prionotus carolinus	--	--	--	--	--	--	--	10	5	9	--	--
Ophidion marginatum	--	--	--	--	--	--	--	--	6	--	--	--
Lepophidium profundorum	--	--	--	--	--	--	--	--	7	--	9	--
Centropristis striata	--	--	--	--	--	--	--	--	9	--	--	--
Ophidiidae	--	--	--	--	--	--	--	--	--	4	--	--
Bothus spp.	--	--	--	--	--	--	--	--	--	10	11	--
Urophycis regia	--	--	--	--	--	--	--	--	--	1	1	6
Ceratoscopelus maderensis	--	--	--	--	--	--	--	--	--	--	7	--
Diaphus spp.	--	--	--	--	--	--	--	--	--	--	--	9

Note: Larvae are ranked in the top 10 or 11 taxa per month according to numbers collected per 10 m^2 of sea surface. Dashes indicate few or no collections of that taxon in that month.

caught with small meshed trawls, pound nets, and traps (Cadrin, 1998). Fishing effort tracks the seasonal distribution, with offshore (i.e., shelf edge) fishing taking place from October to March and inshore (i.e., middle and inner shelf) fishing taking place from April to September.

The shortfin squid belongs to the family Ommastrephidae, a family consisting entirely of oceanic species. It is distributed accordingly in oceanic and shelf edge waters from Geenland to Cape Hatteras (Lange and Sissenwine, 1980). It migrates into shallower waters (10 to 50 m) during summer months; in late fall it moves south and offshore in the area from Georges Bank to Cape Hatteras (Lange and Sissenwine, 1980). Spawning occurs from December to June in offshore waters. Most individuals die following spawning. The species lives up to one year (Hendrickson, 1998). In Middle Atlantic Bight waters, commercial trawl fisheries are concentrated in outer shelf waters from June to September when abundance peaks. The 1986 to 1996 annual catch of shortfin squid averaged 12,800 MT (Hendrickson, 1998). Most commercial fishing is conducted in shelf edge waters with small-mesh trawls.

2.3.2.4 Fishes

Pelagic fishes inhabiting shelf waters north of Cape Hatteras include Atlantic mackerel, bluefish, butterfish, striped bass (*Morone saxatilis*), and herrings such as alewife (*Alosa psuedoharengus*), American shad (*Alosa sapidissima*), Atlantic herring (*Clupea harengus*), Atlantic menhaden (*Brevoortia tyrannus*), and blueback herring (*Alosa aestivalis*). Numerous other pelagics occurring off northern North Carolina include striped and bay anchovies (*Anchoa hepsetus* and *A. mitchilli*, respectively), crevalle jack (*Caranx hippos*), king and Spanish mackerels (*Scomberomorus cavalla* and *S. maculatus*, respectively), and striped and white mullets (*Mugil cephalus* and *M. curema*, respectively) but are not mentioned further because of their lesser economic importance in this region.

All of these pelagic species form schools and migrate seasonally with peaks during various portions of the year. Most of these species are important to recreational and commercial fisheries. As with the demersal fishes, most pelagic species found in the Middle 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 Middle Atlantic Bight is generally a response to seasonal changes in water temperature that trigger southerly or northerly movements by species of southern or northern origin, respectively.

The Atlantic mackerel occurs in two spawning populations in the northwestern Atlantic: a northern population in the Gulf of St. Lawrence that spawns in June and July, and a southern population that spawns in the Middle Atlantic Bight during July and August (Overholtz, 1998b). In the Middle Atlantic Bight, the Atlantic mackerel spends winter months in offshore waters near the shelf edge; in spring, it migrates inshore and to the north. Spawning occurs during this migration in shelf waters. This species is sought by commercial and recreational fishers. Commercial fishing occurs primarily from January through May; recreational fishing occurs mostly from April to October (Overholtz, 1998b). Annual landings in the Middle Atlantic Bight averaged 14,840 MT from 1987 to 1996.

The bluefish is a migratory species occurring in inshore, coastal, and shelf waters. It migrates into the Middle Atlantic Bight during spring, and south or offshore during fall. The bluefish is an important fishery species. Early investigations held that the bluefish spawned during two discrete events: one in the South Atlantic Bight, and the other in the Middle Atlantic Bight. New evidence indicates that spawning is a continuous event, beginning during spring in South Atlantic Bight waters (Cowan et al., 1993; Smith et al., 1994). The bluefish spawns during mid-summer months in waters south of Cape Hatteras; however, young fishes recruit to inshore waters of the Middle Atlantic Bight coast including Long Island Sound (Nyman and

Conover, 1988). This species is important to commercial and recreational fisheries of the region. The 1994 to 1996 average annual commercial landings were 11,400 MT for the eastern U.S., and recreational landings for the Middle Atlantic Bight were 7,400 MT (Terceiro, 1998). Primary commercial gear for bluefish are otter trawl and gill net.

The Middle Atlantic Bight butterfish population migrates northward and inshore in summer. In winter months, the population moves southward and offshore. The butterfish spawns continuously from late January to at least July in the Middle Atlantic Bight (Rotunno and Cowen, 1997). This species exhibits high natural mortality and is prey for many predatory species. It grows rapidly and reaches a maximum age of about 3 years (Rutunno and Cowen, 1997; Overholtz, 1998a). The current Middle Atlantic Bight fishery lands and average of 3,000 MT annually. Otter trawl is the principal gear used in the fishery.

The herring species exhibit two basic spawning patterns: the alewife, American shad, and blueback herring are anadromous, migrating from the sea into freshwater rivers to spawn, whereas Atlantic herring and Atlantic menhaden spawn in continental shelf waters. The alewife is found along the coast of eastern North America from the Gulf of St. Lawrence to South Carolina (Kocik, 1998a). During autumn, most of the population overwinters in waters near the edge of the continental shelf. In spring, the population moves into shelf waters throughout the region. Adults enter coastal rivers and migrate to fresh water to spawn during spring. The American shad is another anadromous species found in shelf waters during summer and fall (Kocik, 1998b). It moves up rivers to spawn during spring. Water temperature is the key environmental determinant of spawning in this species. Temperature may vary within a season, thus timing of the upstream migration may vary slightly from year to year. Alewife and American shad are important to commercial and recreational fisheries in the region. Commercial catches of alewife averaged about 500 MT/yr for the Middle Atlantic Bight since 1994 (Kocik, 1998a). American shad catches, mostly by gill net, have averaged 1,100 MT/yr since 1980 (Kocik, 1998b).

Atlantic herring is most abundant in northern waters of the Gulf of Maine and Georges Bank. The Georges Bank stock overwinters in the New York Bight from December to April. Spawning occurs year-round with peaks in spring and fall. Adult females lay demersal eggs. Spawning probably does not occur offshore of North Carolina (Able and Fahay, 1998). The primary fisheries for this species occur north of New Jersey on Georges Bank and the Gulf of Maine.

The Atlantic menhaden occurs in shelf waters where it forms large schools. The population in the Middle Atlantic Bight migrates northward in summer and back south in fall to overwinter in warm waters. Spawning occurs offshore North Carolina during fall and spring. This species is not fished north of Virginia.

Striped bass is an anadromous species, like alewife, shads, and Atlantic herring. Adult striped bass move upstream in spring to spawn and move back downstream and into shelf waters in late fall, where they remain through winter. Large striped bass populations along the U.S. east coast are associated with major river systems. The population found in the vicinity of the North Carolina sand resource areas is associated with the Roanoke River-Albemarle Sound watersheds (Manooch and Raver, 1984). Nearshore ocean waters from Cape Lookout, NC to Cape Charles, Virginia are wintering grounds for Atlantic coast striped bass populations (USACE, 2000). Overwintering grounds for striped bass include water depths in which the sand resources areas are located (Laney et al., 1999).

2.3.2.5 Sea Turtles

Five sea turtle species may occur in North Carolina coastal waters (Table 2-4). In approximate order of abundance, they are the loggerhead (*Caretta caretta*), Kemp's ridley (*Lepidochelys kempii*), leatherback (*Dermochelys coriacea*), Atlantic green (*Chelonia mydas*), and hawksbill (*Eretmochelys imbricata*) turtles. The loggerhead is the most common turtle in North Carolina. The loggerhead is considered to be a regular nester in North Carolina in contrast to the other sea turtle species (USACE, 2000). Loggerhead and Kemp's ridley turtles may be present year-round, whereas leatherback and Atlantic green turtles are not likely to be present during winter months. The North Carolina coast is a migratory corridor for juvenile and subadult loggerhead, Kemp's ridley, leatherback, and green turtles, which move to northern waters during spring and return south of Cape Hatteras during fall (Keinath et al., 1996; MMS, 1990). Hawksbills are the least common turtle in the area and are likely to occur only as occasional vagrants (Lee and Socci, 1989).

All five sea turtles are protected under the Endangered Species Act of 1973. Leatherbacks and Kemp's ridleys are endangered and loggerheads are threatened. Atlantic green sea turtles also are threatened, except for the Florida breeding population, which is endangered. Due to inability to distinguish between the latter two populations away from the nesting beach, Atlantic green sea turtles are considered endangered wherever they occur in U.S. waters (NMFS, 1996).

Loggerhead Sea Turtle

The loggerhead sea turtle occurs throughout temperate and tropical waters of the Atlantic, Pacific, and Indian Oceans (Dodd, 1988). In the western North Atlantic, it is found in estuarine, coastal, and shelf waters from South America to Newfoundland. This is the only turtle that nests along the North Carolina coast.

Loggerhead turtles are present year-round in North Carolina waters, with peak abundance during spring and fall migrations (Lee and Socci, 1989; Keinath et al., 1996). Benthic immature turtles migrate northward from south of Cape Hatteras during spring, moving south again during fall (Keinath et al., 1996; Marine Turtle Expert Working Group, 1996a).

Four nesting subpopulations of loggerhead turtles have been identified (Marine Turtle Expert Working Group, 1996a). These are 1) the northern subpopulation, extending from North Carolina to northeastern Florida; 2) the south Florida subpopulation; 3) the Florida Panhandle subpopulation; and 4) the Yucatan subpopulation. Ninety percent of loggerhead nesting in the U.S. occurs in south Florida North Carolina is the northern extent of significant loggerhead nesting along the Atlantic coast (Frazier, 1995). The sea turtle nesting and hatching season in North Carolina is reported to extend from May 1 through November 15 of any year (USFWS as cited in USACE, 2000). Annual numbers of loggerhead nests in North Carolina during 1989 to 1995 ranged from 459 to 1,021, with a mean of 729 nests annually (Marine Turtle Expert Working Group, 1996a). The highest nest densities are south of Cape Lookout, with a relatively low density of nests north of Cape Hatteras (MMS, 1990).

Table 2-4. Sea turtle species potentially occurring in coastal North Carolina waters. Species are listed in order of relative abundance.

Common and Scientific Names	Status[a]	Life Stages Present	Seasonal Presence	Nesting Season [b]
Loggerhead sea turtle (*Caretta caretta*)	T	Adults, juveniles, subadults, hatchlings	Year-round (most abundant during spring and fall migrations)	April - September
Kemp's ridley sea turtle (*Lepidochelys kempii*)	E	Juveniles and subadults	Year-round (most abundant during spring and fall migrations)	(no nesting in area)
Leatherback sea turtle (*Dermochelys coriacea*)	E	Adults, juveniles, subadults	April-October	(no nesting in area)
Green sea turtle (*Chelonia mydas*)	T/E[c]	Juveniles and subadults	May-October	(no nesting in area)
Hawksbill sea turtle (*Eretmochelys imbricata*)	E	Juveniles and subadults	Occasional vagrant	(no nesting in area)

[a] Status: E = endangered, T = threatened under the Endangered Species Act of 1973.
[b] Loggerhead sea turtle nesting season as stated by MMS (1990).
[c] Green sea turtles are listed as threatened except for Florida where breeding populations are listed as endangered. Due to inability to distinguish between the two populations away from the nesting beach, green sea turtles are considered endangered wherever they occur in U.S. waters.

After hatching, loggerheads swim offshore and begin a pelagic existence within *Sargassum* rafts, drifting in current gyres for several years (Marine Turtle Expert Working Group, 1996a). At approximately 40 to 60 cm carapace length, juveniles and subadults move into nearshore and estuarine areas, where they become benthic feeders for a decade or more prior to maturing and making reproductive migrations (Carr, 1987).

Loggerhead adults and subadults are generalist carnivores, feeding primarily on nearshore benthic crustaceans (particularly crabs) and mollusks (Dodd, 1988). These turtles generally feed in water depths of 15 m or less (NMFS, 1996), which would occur slightly inshore of the sand resource areas.

Kemp's Ridley Sea Turtle

The Kemp's ridley is the smallest and most endangered of the sea turtles. Its distribution extends from the Gulf of Mexico to Nova Scotia and Newfoundland (Marine Turtle Expert Working Group, 1996b). Adult turtles are found almost exclusively in the Gulf of Mexico, primarily in shallow coastal waters less than 50 m deep (Byles, 1988).

Kemp's ridleys found along the North Carolina coast are juveniles and subadults that use shallow east coast waters as developmental habitat. They move northward along the coast with the Gulf Stream in spring to feed in productive, coastal waters between Georgia and New England (NMFS and USFWS, 1992). These migrants then move southward with the onset of cooler temperatures in late fall and winter. North Carolina is likely to represent the northernmost location for year-round residency of Kemp's ridley juveniles and subadults (Schwartz, 1978; Lutcavage and Musick, 1985; Crouse, 1988).

Nesting of Kemp's ridleys occurs almost entirely at Rancho Nuevo beach, Tamaulipas, Mexico, where 95% of the nests are laid along 60 km of beach (NMFS and USFWS, 1992; Weber, 1995). In the U.S., nesting occurs infrequently on Padre and Mustang Islands in south Texas and in a few other locations (Marine Turtle Expert Working Group, 1996b).

After emerging, Kemp’s ridley hatchlings swim offshore to inhabit *Sargassum* mats and drift lines associated with convergences, eddies, and rings. The hatchlings feed at the surface and are dispersed widely by Gulf and Atlantic surface currents. After reaching a size of about 20 to 60 cm carapace length, juveniles enter shallow coastal waters and become benthic carnivores (Marine Turtle Expert Working Group, 1996b). This is the life stage that could be present in the project area. Kemp’s ridleys prefer crabs, but also occasionally eat mollusks, shrimps, dead fishes, and vegetation (Mortimer, 1982; Lutcavage and Musick, 1985; Shaver, 1991; Burke et al., 1993; Werner and Landry, 1994).

Leatherback Sea Turtle

The leatherback sea turtle is a circumglobal species that inhabits waters of the western Atlantic Ocean from Newfoundland to northern Argentina. The leatherback is the largest living turtle (Eckert, 1995), and with its unique deep-diving abilities (Eckert et al., 1986) and wide-ranging migrations, is considered the most pelagic of the sea turtles (Marquez, 1990).

Leatherback turtles occur in North Carolina waters primarily from April through October, with occasional sightings during winter (Lee and Palmer, 1981). Keinath et al. (1996) reported leatherback sightings during aerial surveys in May, July, August, October, and November. The species has been reported as occurring in shallow coastal waters but not usually near shore (Lee and Socci, 1989). Lee and Palmer (1981) reported its occurrence in waters from 16 to 48 km offshore.

Leatherbacks nest on coarse-grained, high-energy beaches in tropical latitudes (Eckert, 1995). Florida is the only location in the continental U.S. where significant leatherback nesting occurs. Very little is known of the pelagic distribution of hatchling and/or juvenile leatherback turtles.

Adult leatherbacks feed in the water column, primarily on cnidarians (medusae, siphonophores) and tunicates (salps, pyrosomas) (Eckert, 1995). The turtles are sometimes observed in association with jellyfishes, but actual feeding behavior has only occasionally been documented. Foraging has been observed at the surface, but also is likely to occur at depth (Eckert, 1995).

Atlantic Green Sea Turtle

The Atlantic green sea turtle has a circumglobal distribution in tropical and subtropical waters. In the U.S., it occurs in Caribbean waters around the U.S. Virgin Islands and Puerto Rico, and along the mainland coast from Texas to Massachusetts. Adult green turtles are typically found in shallow tropical and subtropical waters, particularly in association with seagrass beds (NMFS and USFWS, 1991).

Most green sea turtles along the North Carolina coast are juveniles and subadults, because adults usually do not migrate from their preferred habitat (tropical/subtropical seagrass beds) except to nest. Juveniles and subadults may use shallow, coastal waters along the Atlantic coast as developmental habitat. These turtles have been sighted in North Carolina oceanic waters and sounds from May through October (Lee and Palmer, 1981; Lee and Socci, 1989).

The primary nesting sites in U.S. Atlantic waters are high-energy beaches along the east coast of Florida, with additional sites in the U.S. Virgin Islands and Puerto Rico (NMFS and USFWS, 1991). A confirmed Atlantic green sea turtle nest has been recorded near the study area, but the species is not considered to be a regular nester (USACE, 2000). Hatchlings swim out to sea and enter a pelagic stage in *Sargassum* mats associated with convergence zones.

Adult green turtles commonly feed on seagrasses, algae, and associated organisms, using reefs and rocky outcrops near seagrass beds for resting areas. The major feeding grounds in U.S. waters are located in Florida. In coastal waters, green turtles feed mainly on algae and the seagrass *Zostera marina* (Burke et al., 1992). Juveniles go through an omnivorous stage of 1 to 3 years (NMFS and USFWS, 1991).

Hawksbill Sea Turtle

Hawksbill sea turtles (*Eretmochelys imbricata)* occur in tropical and subtropical seas of the Atlantic, Pacific, and Indian Oceans. In the western Atlantic, hawksbill turtles are generally found in clear tropical waters near coral reefs, including the Caribbean, the Bahamas, the Florida Keys, and the southwestern Gulf of Mexico. Hawksbills are rarely sighted north of Florida. They are the least frequently reported species in North Carolina coastal waters and are likely to be present only as occasional vagrants (Lee and Socci, 1989). A fishery for this species once existed in North Carolina (True, 1887), indicating that they were more abundant historically.

Nesting areas for hawksbills in the Atlantic are found in the U.S. Virgin Islands, Puerto Rico, and south Florida. Within the continental U.S., nesting beaches are restricted to the southeastern coast of Florida (i.e., Volusia through Dade Counties) and the Florida Keys (Monroe County), as noted by Meylan (1992) and the NMFS and USFWS (1993). No hawksbill nesting occurs near the project area.

Adult hawksbills typically are associated with coral reefs and similar hard bottom areas, where they forage on sponges. Hatchlings are pelagic, drifting with *Sargassum* rafts. Juveniles shift to a benthic foraging existence in shallow waters, progressively moving to deep waters as they grow and become capable of deeper dives for sponges.

2.3.2.6 Marine Mammals

About 30 marine mammal species may occur off North Carolina (Table 2-5). However, only a few species are typically found in near-coastal waters. Marine mammals listed as endangered or threatened under the Endangered Species Act of 1973 are discussed first. A subsequent section covers non-listed species. All marine mammals are protected under the Marine Mammal Protection Act of 1972.

Listed Species

Three species of endangered cetaceans are likely to occur in coastal North Carolina waters during at least some part of the year. They are the fin whale, *Balaenoptera physalus;* humpback whale, *Megaptera novaeangliae*; and northern right whale, *Eubalaena glacialis*. There is no “resident” population of any of these whales in the study region. Fin whales are likely to be present only during winter months. Humpback and northern right whales would be present only as transients during spring and fall migrations. One additional cetacean (the harbor porpoise, *Phocoena phocoena*), occurs seasonally in coastal waters and is a candidate for listing as a threatened species. One endangered sirenian, the Florida manatee (*Trichechus manatus latirostris*), may be present in coastal North Carolina waters during summer months. No critical habitat for listed marine mammals has been designated in or near the project area.

The project area is within the distributional range of three other endangered cetaceans (the blue whale, *B. musculus*; sei whale, *B. borealis*; and sperm whale, *Physeter macrocephalus*), but they are considered unlikely to be present. The sperm whale is a deepwater species (Winn, 1982; Roden, 1998), and blue and sei whales would not be expected to occur commonly off North Carolina (MMS, 1990; Waring et al., 1999).

Table 2-5. Species of marine mammals potentially occurring in North Carolina coastal waters. Key: (**X**) presence likely during at least some season; (**o**) presence possible but unlikely due to geographic range, preference for deeper waters, or uncommon occurrence.

Scientific Name	Common Name	Status[a]	Presence
ORDER CETACEA			
SUBORDER MYSTICETI	**BALEEN WHALES**		
Family Balaenidae	**Right and Bowhead Whales**		
Eubalaena glacialis	Northern right whale	E, S	**X**
Family Balaenopteridae	**Rorquals**		
Balaenoptera musculus	Blue whale	E, S	**o**
Balaenoptera edeni	Bryde's whale	none	**o**
Balaenoptera physalus	Fin whale	E, S	**X**
Megaptera novaeangliae	Humpback whale	E, S	**X**
Balaenoptera acutorostrata	Minke whale	none	**o**
Balaenoptera borealis	Sei whale	E, S	**o**
SUBORDER ODONTOCETI	**TOOTHED WHALES**		
Family Physeteridae	**Sperm Whales**		
Kogia simus	Dwarf sperm whale	none	**o**
Kogia breviceps	Pygmy sperm whale	none	**o**
Physeter macrocephalus	Sperm whale	E, S	**o**
Family Ziphiidae	**Beaked Whales**		
Mesoplodon densirostris	Blainville's beaked whale	S	**o**
Ziphius cavirostris	Cuvier's beaked whale	S	**o**
Mesoplodon europaeus	Gervais' beaked whale	S	**o**
Mesoplodon mirus	True's beaked whale	S	**o**
Family Delphinidae	**Dolphins**		
Stenella frontalis	Atlantic spotted dolphin	none	**X**
Tursiops truncatus	Bottlenose dolphin	none	**X**
Delphinus delphis	Common dolphin	S	**o**
Pseudorca crassidens	False killer whale	none	**o**
Lagenodelphis hosei	Fraser's dolphin	none	**o**
Orcinus orca	Killer whale	none	**o**
Stenella attenuata	Pantropical spotted dolphin	none	**X**
Feresa attenuata	Pygmy killer whale	none	**o**
Globicephala macrorhynchus	Short-finned pilot whale	S	**o**
Globicephala melas	Long-finned pilot whale	S	**o**
Grampus griseus	Risso's dolphin	none	**o**
Steno bredanensis	Rough-toothed dolphin	none	**o**
Stenella longirostris	Spinner dolphin	none	**o**
Stenella coeruleoalba	Striped dolphin	none	**o**
Family Phocoenidae	**Porpoises**		
Phocoena phocoena	Harbor porpoise	C,S	**o**
ORDER CARNIVORA			
SUBORDER PINNIPEDIA	**SEALS AND SEA LIONS**		
Phoca vitulina	Harbor seal	none	**o**
ORDER SIRENIA	**MANATEES AND DUGONGS**		
Trichechus manatus latirostris	West Indian manatee	E	**o**

[a] Status: E = endangered and C = candidate for listing under the Endangered Species Act of 1973; S = strategic stock under the Marine Mammal Protection Act of 1972, as indicated by Waring et al. (1999).

Fin Whale (endangered). Fin whales range from the Arctic to the Greater Antilles, and animals off the eastern U.S. to Canada constitute a single stock (Donovan, 1991). They are among the largest and fastest baleen whales (Winn, 1982). This species occurs widely off New England and the Mid-Atlantic coast throughout the year, with concentrations from Cape Cod north in summer and from Cape Cod south in winter (Blaylock et al., 1995). They have been sighted off North Carolina only from January to early April, with most sightings during winter (Lee and Socci, 1989). Fin whales typically are usually found inshore of the continental shelf break and may occur near shore (Winn, 1982; MMS, 1990). This species feeds on krill, planktonic crustaceans, and schooling fishes such as herring and capelin. Mating and calving occurs from November to March.

Humpback Whale (endangered). Humpback whales range from the Arctic to the West Indies. During summer, there are at least five geographically distinct feeding aggregations in the northern Atlantic (Blaylock et al., 1995). During fall, humpbacks migrate south to the Caribbean where calving and breeding occurs from January to March (Blaylock et al., 1995). Aerial surveys during the Cetacean and Turtle Assessment Program (CETAP) detected only a few humpback whale sightings from New Jersey southward during any season (Winn, 1982). However, subsequently there have been numerous sightings and strandings off the Mid-Atlantic and southeastern U.S. coast, particularly during winter and spring (Swingle et al., 1993; Wiley et al., 1995). Most of the stranded animals were juveniles, suggesting that the area may be an important developmental habitat (Wiley et al., 1995). Humpbacks feed largely on euphausiids and small fishes such as herring, capelin, and sand lance, and their distribution has been largely correlated to prey species and abundance (Blaylock et al., 1995). Calving and breeding occurs in the Caribbean from January to March. Critical habitats have been identified in the western Gulf of Maine and the Great South Channel (Massachusetts).

Northern Right Whale (endangered). Northern right whales range from Iceland to eastern Florida, primarily in coastal waters. This is the rarest of the world's baleen whales, with a North Atlantic population of between 325 and 350 individuals (Kraus et al., 1993). Coastal waters of the southeastern U.S. (off Georgia and northeastern Florida) are important wintering and calving grounds for northern right whales, while the waters around Cape Cod and Great South Channel are used for feeding, nursery, and mating during summer (Kraus et al., 1988; Schaeff et al., 1993). From June to September, most animals are found feeding north of Cape Cod. Southward migration occurs offshore from mid-October to early January (Kraus et al., 1993). Migration northward along the North Carolina coast may begin as early as January, but occurs primarily during March and April (Lee and Socci, 1989; MMS, 1990). Designated critical habitat for the northern right whale includes portions of Cape Cod Bay and Stellwagen Bank and the Great South Channel (off Massachusetts) and waters adjacent to the coasts of Georgia and northeastern Florida.

Harbor Porpoise (candidate for threatened listing). The Gulf of Maine/Bay of Fundy stock of the harbor porpoise was proposed for threatened status in 1993 but the proposal was subsequently withdrawn by the NMFS in 1999. The stock remains on the “candidate” species list. Candidate species do not receive substantive or procedural protection under the Endangered Species Act. The candidate species list serves to notify the public that NMFS has concerns regarding these species that may warrant listing in the future, and it facilitates voluntary conservation efforts.

Harbor porpoises are found in cool temperate and subpolar waters of the Northern Hemisphere (Blaylock et al., 1995). Harbor porpoises were the most common odontocete species sighted on the continental shelf during CETAP (Winn, 1982). However, they were primarily concentrated in New England waters, well to the northeast of the North Carolina coastline (Winn, 1982). As the name implies, harbor porpoises are typically found in shallow water, most often in bays and harbors, although they occasionally travel over deeper offshore waters (Jefferson et al., 1993). During summer, these animals are concentrated in Canada and the northern Gulf of Maine. During fall (October to December) and spring (April to June), they are widely distributed from Maine to North Carolina (Blaylock et al., 1995). Little is known of their distribution during winter (December through March). Harbor porpoises are believed to feed on pelagic schooling fishes such as herring and mackerel (Gaskin, 1992).

Florida Manatee (endangered). The West Indian manatee is one of the most endangered marine mammals in coastal waters of the U.S. In the southeastern U.S., manatees are limited primarily to Florida and Georgia. This group constitutes a separate subspecies called the Florida manatee (*Trichechus manatus latirostris*) that appears to be divided into at least two virtually separate populations – one centered along the Atlantic coast and the other on the Gulf coast of Florida (U.S. Fish and Wildlife Service [USFWS], 1996). Despite concerted research, it has not been possible to develop a reliable estimate of manatee abundance in Florida. The highest single-day count of manatees from an aerial survey is 1,856 animals in January 1992 (Ackerman, 1995).

During winter months, the manatee population confines itself to coastal waters of the southern half of peninsular Florida and to springs and warm water outfalls as far north as southeastern Georgia (USFWS, 1996). As water temperatures rise in spring, manatees disperse from winter aggregation areas. During summer, they may migrate as far north as coastal Virginia (USFWS, 1996). Manatees inhabit both salt and fresh water of sufficient depth (1.5 m to usually less than 6 m) throughout their range. They are usually found in canals, rivers, estuarine habitats, and saltwater bays, but on occasion have been observed as much as 3.7 miles off the Florida coast (USFWS, 1996).

Based on their known distribution patterns, a few Florida manatees occasionally could be present in North Carolina waters during summer months. Lee and Socci (1989) report occurrences between late June and early November. However, because these animals tend to stay in shallow estuarine waters rather than the open ocean, they are considered unlikely to be present in the project area.

Critical habitat for this endangered species has been designated by the USFWS. All of the critical habitat areas are in peninsular Florida, predominantly along the southwest and southeast coasts (USFWS, 1996).

Non-Listed Species

The most common non-listed marine mammal occurring in North Carolina coastal waters is the bottlenose dolphin (*Tursiops truncatus*), which may be present year-round (Winn, 1982; Kenney, 1990). Bottlenose dolphins in the western Atlantic range from Nova Scotia to Venezuela (Waring et al., 1999). This species is distributed worldwide in temperate and tropical inshore waters. Along the U.S. Atlantic coast, there are two distinct stocks: coastal and offshore (Duffield et al., 1983; Duffield, 1986; Mead and Potter, 1995). The two forms differ in distribution, morphometrics, parasite loads, prey, and DNA markers (Mead and Potter, 1995; Hoelzel et al., 1998). North of Cape Hatteras, the coastal stock is associated with water depths less than 25 m (Kenney, 1990). Therefore, bottlenose dolphins in the project area would most likely represent the coastal stock. Some portion of the coastal stock apparently resides south of Cape Hatteras during winter and migrates as far north as New Jersey during summer (Waring et al., 1999). The NMFS is currently studying Atlantic coastal bottlenose dolphins to determine whether they represent a single migratory stock or a series of multiple stocks (Waring et al., 1999). Bottlenose dolphins feed on shrimps and fishes. Mating and calving occur from

February to May. The calving interval is 2 to 3 years. They are found in groups of up to several hundred individuals.

Also potentially occurring in shelf and coastal waters is the Atlantic spotted dolphin (*Stenella frontalis*). Atlantic spotted dolphins range from New Jersey to Venezuela, primarily in warm temperate and tropical waters. This species inhabits the continental shelf and slope, though southern populations occasionally come into shallow coastal waters (Waring et al., 1999). Favored prey include herrings, anchovies, and carangid fishes. Mating has been observed in July, with calves born offshore. Atlantic spotted dolphins often occur in groups of up to 50 individuals. Stock structure in the western North Atlantic is unknown.

Two non-listed species of mysticetes may occur in North Carolina waters: Bryde's whale (*B. edeni*), and minke whale (*B. acutorostrata*). Both are predominantly found in more northerly waters (Winn, 1982) and are infrequently sighted or stranded in North Carolina (MMS, 1990).

Non-listed odontocetes potentially occurring off the North Carolina coast but typically in deeper waters (along the shelf edge and beyond) include dwarf and pygmy sperm whales (*Kogia simus* and *K. breviceps*), common dolphin (*Delphinus delphis*), false killer whale (*Pseudorca crassidens*), pantropical spotted dolphin (*Stenella attenuata*), pygmy killer whale (*Feresa attenuata*), long-finned pilot whale (*Globicephala melas*), short-finned pilot whale (*G. macrorhynchus*), Risso's dolphin or grampus (*Grampus griseus*), rough-toothed dolphin (*Steno bredanensis*), spinner dolphin (*Stenella longirostris*), and striped dolphin (*Stenella coeruleoalba*) (Winn, 1982; Roden, 1998; Waring et al., 1999). Though beaked whales (*Mesoplodon* spp. and *Ziphius cavirostris*) also may occur off the Mid-Atlantic, their distribution at sea is poorly known and they are believed to be principally deep, offshore species. Shelf species potentially occurring in the area but generally found in more northern waters include Fraser's dolphin (*Lagenodelphis hosei*), and the previously discussed harbor porpoise. The killer whale (*Orcinus orca*) also may occur on the shelf or slope (Winn, 1982) but is considered uncommon or rare in U.S. waters (Blaylock et al., 1995).

One non-listed pinniped species, the harbor seal (*Phoca vitulina*), also may occur off the North Carolina coast. Harbor seals normally occur year-round in coastal waters of Canada and New England, moving south to winter (Blaylock et al., 1995). Occurrences off North Carolina would be most likely from November through May.

3.0 REGIONAL GEOMORPHIC CHANGE

Nearshore sediment transport processes influence the evolution of shelf sedimentary environments to varying degrees depending on temporal and spatial response scales. Although micro-scale processes, such as turbulence and individual wave orbital velocities, determine the magnitude and direction of individual grain motion, variations in micro-scale processes are considered noise at regional-scale and only contribute to coastal response in an average sense. By definition, regional-scale geomorphic change refers to the evolution of depositional environments for large coastal stretches (10 km or greater) over extended time periods (decades or greater) (Larson and Kraus, 1995). An underlying premise for modeling long-term morphologic change is that a state of dynamic equilibrium is reached as a final stage of coastal evolution. However, interaction between the scale of response and forces causing change may result in a net sediment deficit or surplus within a system, creating disequilibrium. This process defines the evolution of coastal depositional systems.

Topographic and hydrographic surveys of coastal and nearshore morphology provide a direct source of data for quantifying regional geomorphology and change. Historically, hydrographic data have been collected in conjunction with regional shoreline position surveys by the U.S. Coast and Geodetic Survey (USC&GS); currently Coast and Geodetic Survey of the National Ocean Service [NOS], National Oceanic and Atmospheric Administration [NOAA]). Comparison of digital bathymetric data for the same region but different time periods provides a method for calculating net sediment movements into (accretion) and out of (erosion) an area of study. Coastal scientists, engineers, and planners often use this information for estimating the magnitude and direction of sediment transport, monitoring engineering modifications to a beach, examining geomorphic variations in the coastal zone, establishing coastal erosion setback lines, and verifying shoreline change numerical models. The purpose of this portion of the study is to document patterns of geomorphic change throughout the sand resource areas and quantify the magnitude and direction of net sediment transport over the past 100 to 120 years. These data, in combination with wave and current measurements and model output, provide a temporally integrated technique for evaluating the potential physical impacts of offshore sand mining on sediment transport dynamics.

3.1 SHORELINE POSITION CHANGE

Creation of an accurate map is always a complex surveying and cartography task, but the influence of coastal processes, relative sea level, sediment source, climate, and human activities make shoreline mapping especially difficult. In this study, shoreline surveys are used to define landward boundaries for bathymetric surfaces and to document net shoreline movements between specified time periods. Consequently, net change results can be compared with wave model output and nearshore sediment transport simulations to evaluate cause and effect. Results integration provides a direct method of documenting potential environmental impacts related to sand mining on the OCS.

3.1.1 Previous Studies

Beaches along the Outer Banks of North Carolina consist primarily of sand, shell, and gravel reworked from Tertiary and Quaternary Coastal Plain sediment (Riggs et al., 1995; Pilkey et al., 1998). Nearshore sediment from Cape Hatteras north to Virginia is predominantly fine gray sand (Figure 3-1; Inman and Dolan, 1989); however, sections of beach between Nags Head and the False Cape contain high concentrations of non-carbonate gravel (Pilkey et al.,

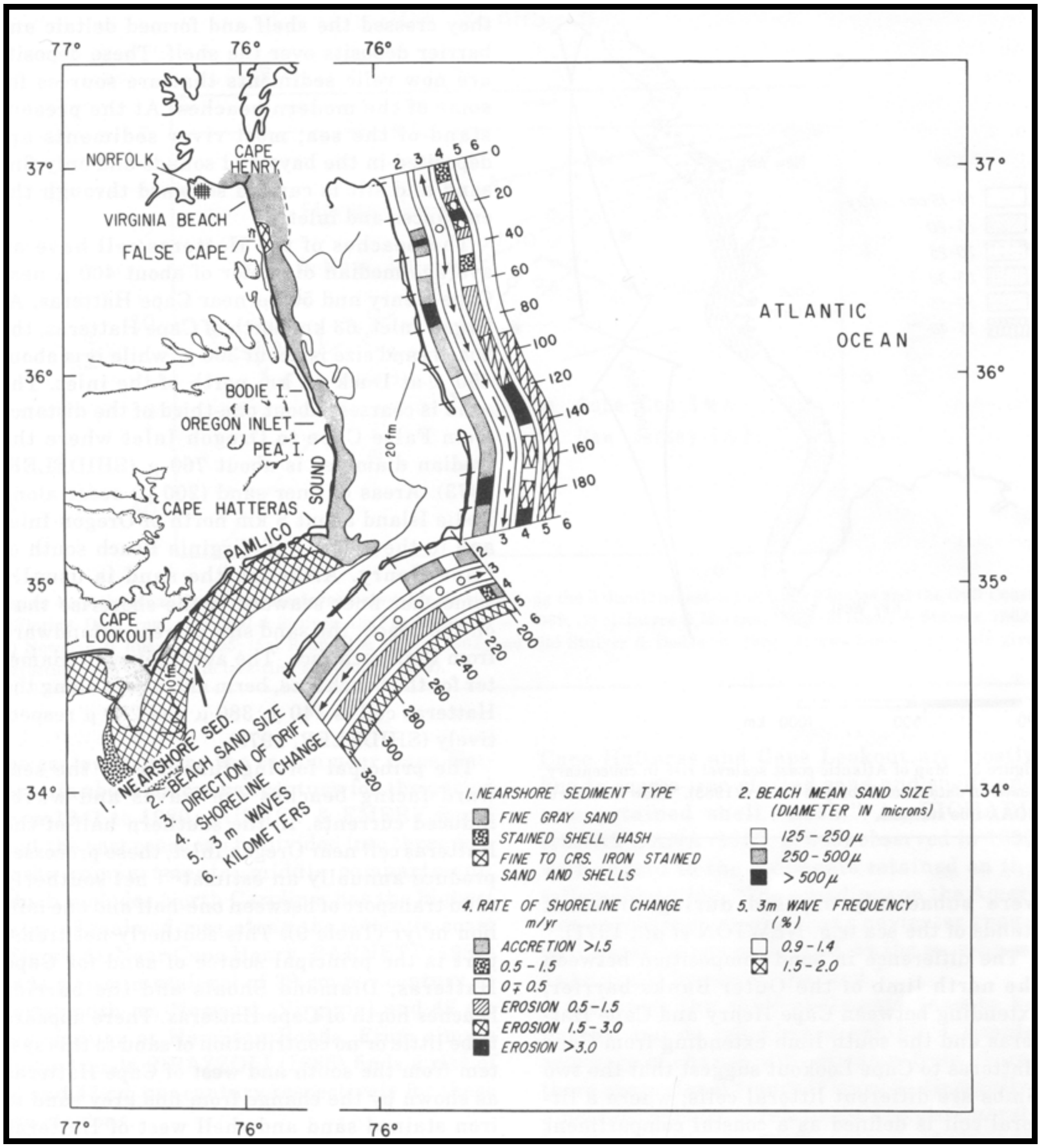

Figure 3-1. Sediment type, shoreline change, and direction of net littoral drift along the Outer Banks of North Carolina (from Inman and Dolan, 1989).

1998). Gravel deposits are associated with ancient river channels that underlie the barrier beaches and outcrop on the shoreface. These deposits are located outside the immediate study area (Kitty Hawk to Oregon Inlet).

Historical shorelines for the North Carolina coast north of Cape Hatteras were mapped by Everts et al. (1983) as part of a cooperative analysis of shoreline change between the USACE and the NOS. The primary benefit of these data was to document shoreline response since the mid-1800s to natural processes and engineering activities (e.g., beach nourishment, jetty and groin placement). Langfelder (1970) and Dolan et al. (1979) extracted shorelines from aerial photography dating from 1945 to document short-term trends in beach response (Figure 3-1). The average rate of shoreline retreat between False Cape and Oregon Inlet was determined to be about 1.4 m/yr. However, the beaches adjacent to Oregon Inlet illustrate retreat rates as high as 5 m/yr (Inman and Dolan, 1989). Everts et al. (1983) documented shoreline changes between 1849 and 1980 using historical maps and aerial photography. Net recession rates between Kitty Hawk and Oregon Inlet increased from 0 to 3 m/yr, respectively, illustrating the influence of inlet processes on shoreline response (Figure 3-2). Overall, the dominant direction of transport at the inlet was north to south, resulting in southward growth of Bodie Island at a rate of about 23 m/yr (Figure 3-3; Dolan and Smith, 2003). Between 1991 and 2001, southward migration of Bodie Island increased to a rate of about 60 m/yr (USACE, 2002), resulting in a net migration rate of about 27 m/yr since 1849.

More recently, Overton et al. (1999) compiled shoreline positions from maps and aerial photography for the period 1940 to 1995 for Dare County beaches. Figure 3-4 illustrates the trend of long-term change between Southern Shores and Nags Head. Approximately 35% of the coast was accreting and 65% was eroding. The largest recession rate was about 3.5 m/yr near Nags Head.

3.1.2 Shoreline Position Data Base

For the present study, six outer coast shoreline surveys, conducted by the USC&GS (predecessor to NOS) in 1849/51, 1915/16, 1949, 1962, 1975, and 1980 (Table 3-1), were used to quantify historical shoreline change. The 1849/51 and 1915/16 were completed as field surveys using standard planetable techniques, whereas the final four shoreline surveys were compiled from interpreted aerial photography.

When determining shoreline position change, all data contain inherent uncertainties associated with field and laboratory compilation procedures. These potential errors should be quantified to gage the significance of measurements used for engineering/research applications and management decisions. Table 3-2 summarizes uncertainty estimates for shoreline data sets used in this study. Because these individual potential errors are considered standard deviations, root-mean-square uncertainties are calculated as a realistic assessment of combined potential error.

Positional uncertainties for each shoreline can be calculated using the information in Table 3-2; however, change analysis requires comparing two shorelines from the same geographic area but different time periods. Table 3-3 is a summary of potential errors associated with change analyses computed for specific time intervals. As expected, maximum positional uncertainties are aligned with the oldest shorelines (1849/51 and 1915/16) at smallest scale (1:20,000 and 1:40,000), but most change estimates for the study area document shoreline advance or retreat greater than these values.

3.1.3 Historical Change Trends

Regional change analyses provided a without-project assessment of shoreline response for comparison with predicted changes in wave-energy focusing at the shoreline resulting from potential offshore sand dredging activities. It differs from previous analyses in that continuous measurements of shoreline change are provided at 50-m alongshore intervals for the period 1849/51 to 1980 (see Appendix A). As such, model results (wave and sediment transport) at discrete intervals along the coast can be compared with historical data to develop process/response relationships for evaluating potential impacts. The following discussion focuses on incremental changes in shoreline response (1849/51 to 1915/16, 1915/16 to 1949, 1949 to 1980) relative to net, long-term trends (1849/51 to 1980).

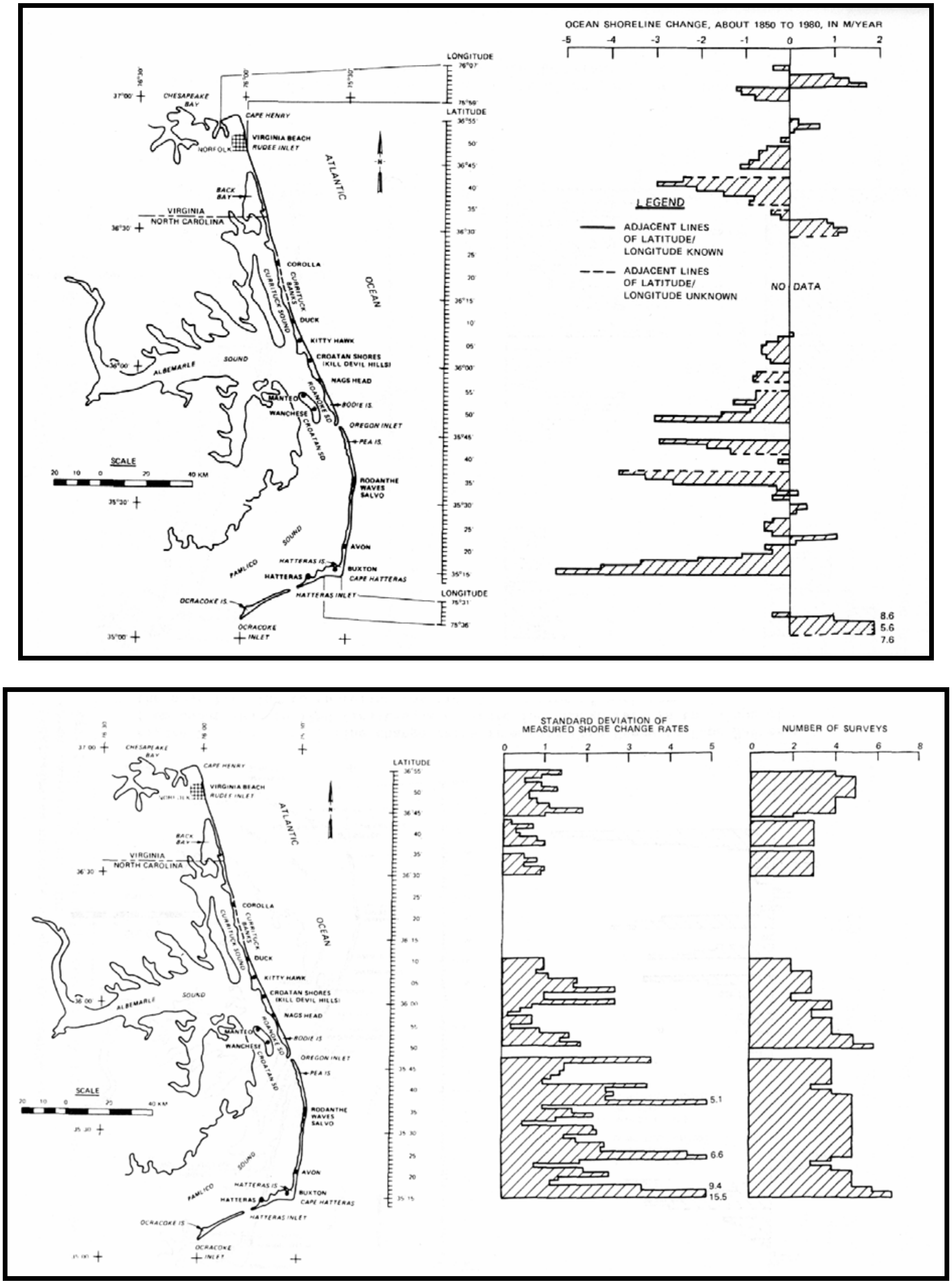

Figure 3-2. Shoreline change rates and standard deviations of position change from about 1850 to 1980 between Cape Henry, VA and Cape Hatteras, NC (from Everts et al., 1983).

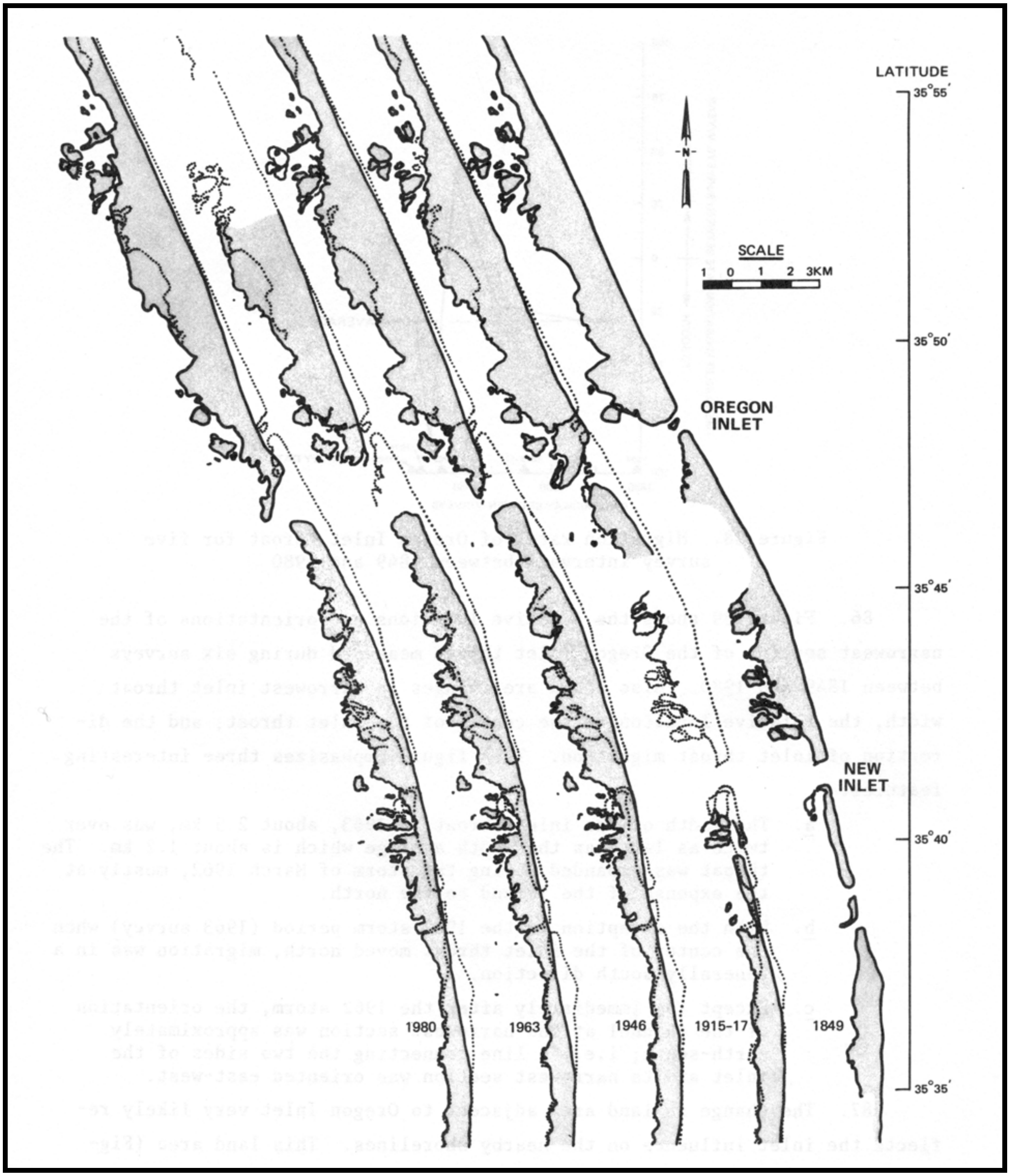

Figure 3-3. Shoreline changes adjacent to Oregon Inlet, NC for five surveys between 1852 and 1980 (from Everts et al., 1983)

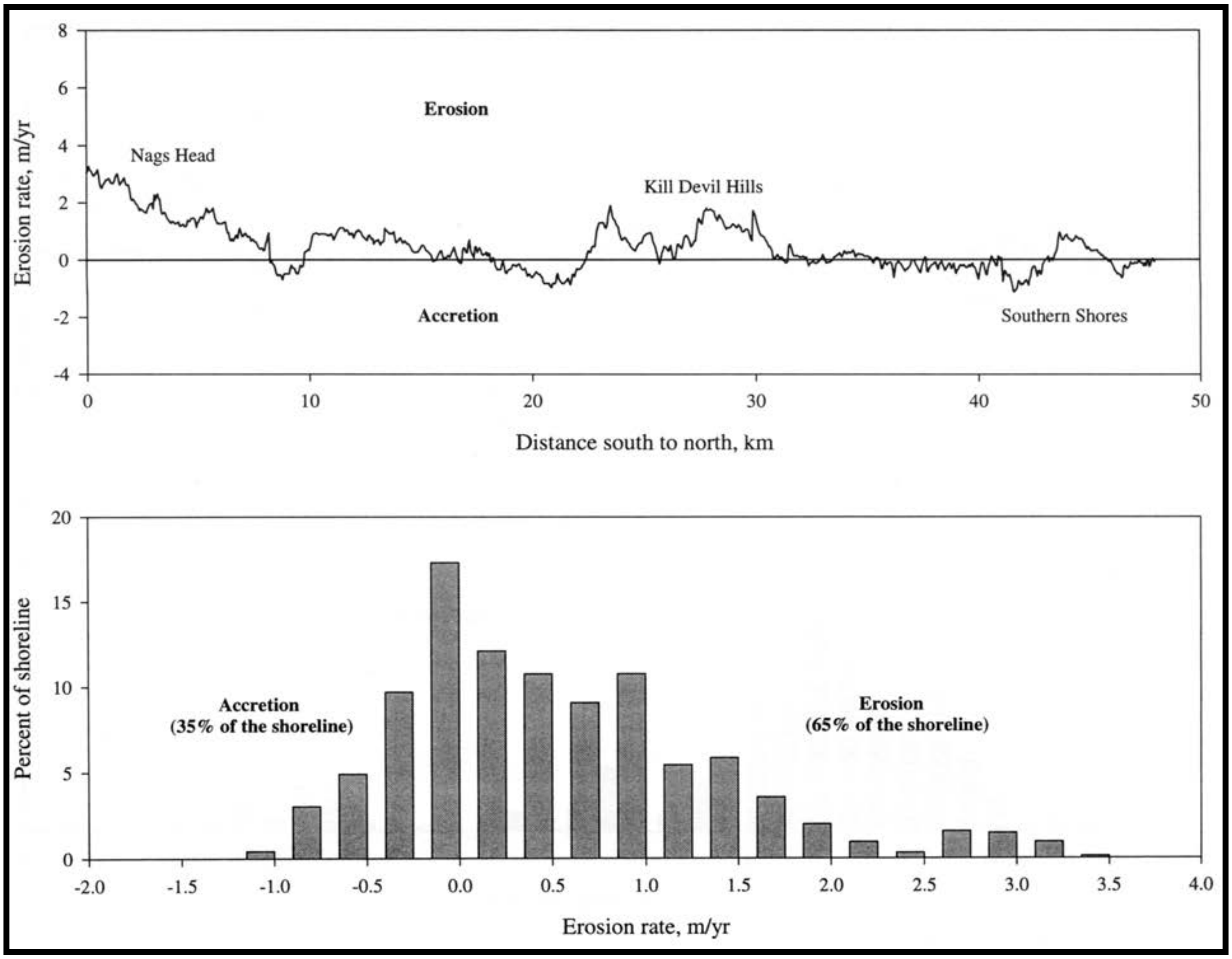

Figure 3-4. Erosion rate analysis for the period 1940 to 1992/95 for Dare County, NC (from Overton et al., 1999).

3.1.3.1 1849/51 to 1949

Shoreline response along the ocean beaches between the USACE FRF Pier and Oregon Inlet for the period 1849/51 to 1915/16 illustrates a large area of shoreline advance north of Nags Head (up to about 3 m/yr; average change about 1.1 m/yr) and shoreline recession south of this point to Oregon Inlet (average change about -1.2 m/yr; Figure 3-5). Concurrently, the sand spit along the northern margin of Oregon Inlet advanced to the southeast at a rate of about 36 m/yr. The inlet responded by migrating to the southeast, forcing northern Pea Island to erode to the southeast at about 31 m/yr. South of Oregon Inlet (northern 2.8 km of Pea Island), average shoreline recession was about 5.2 m/yr, approximately 1.6 times the average recession rate for an equivalent distance north of the inlet (-3.3 m/yr). Between 1915/16 and 1949, shoreline recession continued to be the dominant trend between Nags Head and Oregon Inlet (average recession of 1.7 m/yr; Figure 3-6).

Table 3-1. Summary of shoreline source data characteristics for the North Carolina coast between Kitty Hawk and Oregon Inlet.

Date	Data Source	Comments and Map Numbers
1849/51	USC&GS Topographic Maps 1:20,000 (T-292, T-351, T-354)	First regional shoreline survey throughout study area using standard planetable surveying techniques.
1915/16	USC&GS Topographic Maps 1:40,000 (T-3538)	Second regional shoreline survey (1:40,000 reconnaissance scale) along the seaward coast of the study area using standard planetable surveying techniques.
May - Dec 1949	USC&GS Topographic Maps 1:20,000 (T-9159, T-9160, T-9278)	First regional shoreline survey completed using aerial photos; about 3 km north of Nags Head to Oregon Inlet.
May 1962	USC&GS Topographic Maps 1:10,000 (T-11665, T-11672, T-12140)	Maps produced from interpreted aerial photography flown in May 1962.
May 1975	USC&GS Topographic Maps 1:10,000 (TP-00887, TP-00889)	Maps produced from interpreted aerial photography flown in May 1975.
March 1980	NOS-USACE Shoreline Change Maps 1:24,000 (Base Maps 51-55)	Maps produced from interpreted aerial photography flown in March 16, 1980 (see Everts et al., 1983).

Table 3-2. Positional uncertainty estimates associated with North Carolina shoreline surveys.

Traditional Engineering Field Surveys (1849/51, 1915/16)		
Location of rodded points	± 1 m	
Location of plane table	± 2 to 3 m	
Interpretation of high-water shoreline position at rodded points	± 3 to 4 m	
Error due to sketching between rodded points	up to ± 5 m	
Cartographic Errors (all maps for this study)	**Map Scale**	
	1:10,000	1:20,000
Inaccurate location of control points on map relative to true field location	up to ± 3 m	up to ± 6 m
Placement of shoreline on map	± 5 m	± 10 m
Line width for representing shoreline	± 3 m	± 6 m
Digitizer error	± 1 m	± 2 m
Operator error	± 1 m	± 2 m
Aerial Surveys (1949, 1962, 1975, 1980)	**Map Scale**	
	1:10,000	1:20,000
Delineating high-water shoreline position	± 5 m	± 10 m
Sources: Shalowitz, 1964; Ellis 1978; Anders and Byrnes, 1991; Crowell et al., 1991.		

Table 3-3. Maximum root-mean-square uncertainties for North Carolina shoreline change data.

	1915/16	1949	1962	1975	1980
1849/51	± 31.6[1]	± 22.6	± 17.3	± 17.3	± 25.8
	(± 0.5)[2]	(± 0.2)	(± 0.2)	(± 0.1)	(± 0.2)
1915/16		± 32.4	± 29.0	± 29.0	± 34.1
		(± 1.0)	(± 0.6)	(± 0.5)	(± 0.5)
1949			± 18.7	± 18.7	± 26.7
			(± 1.4)	(± 0.7)	(± 0.9)
1962				± 11.8	± 22.4
				(± 0.9)	(± 1.2)
1975					± 22.4
					(± 4.5)

Magnitude of potential error associated with high-water shoreline position change (m); [2] Rate of potential error associated with high-water shoreline position change (m/yr).

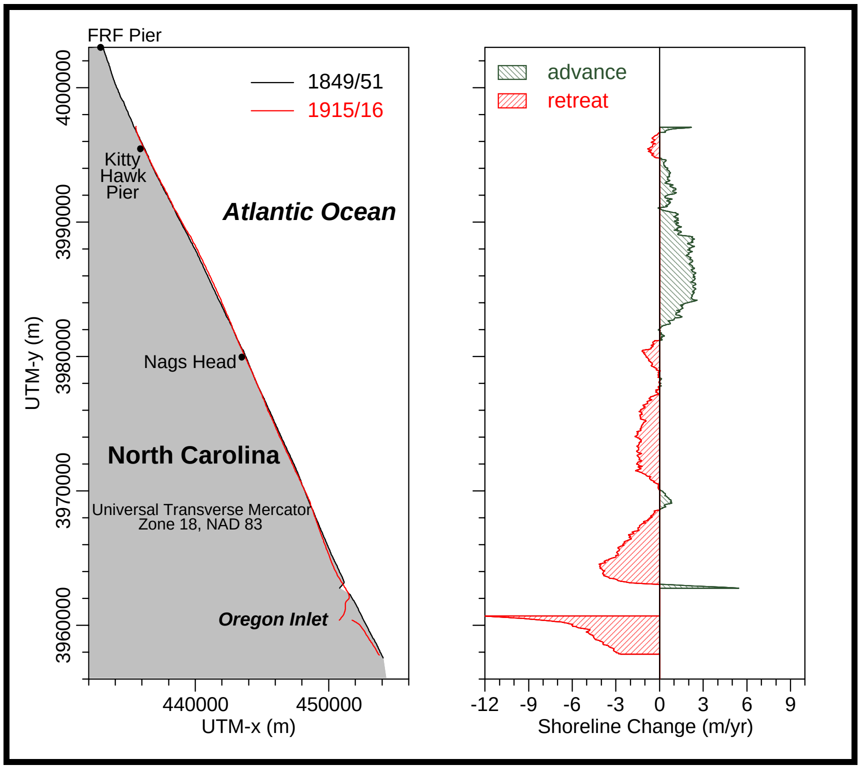

Figure 3-5. Shoreline position and change between the FRF Pier and Oregon Inlet, NC, 1849/51 to 1915/16.

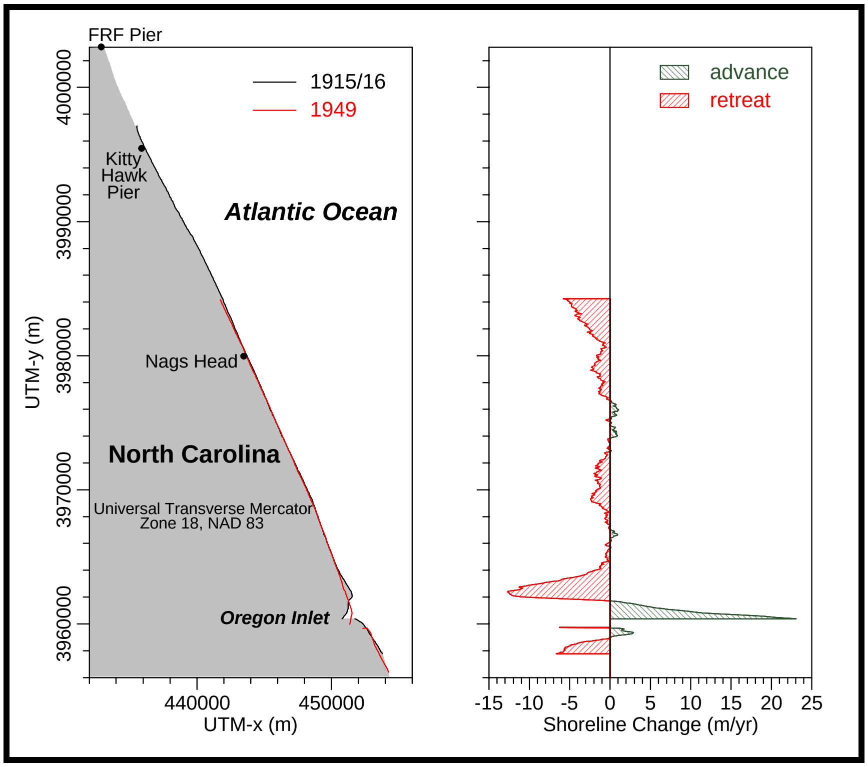

Figure 3-6. Shoreline position and change between the Nags Head and Oregon Inlet, NC, 1915/16 to 1949.

However, greatest changes occurred adjacent to Oregon Inlet as it continued to migrate to the southeast at approximately 20 m/yr. The southern 1.3 km of Bodie Island advanced at an average rate of 8.4 m/yr, but the shoreline 3.8 km north of this point receded at a rate of 4.7 m/yr, illustrating the influence of inlet dynamics on beach response. For the 100-yr record between 1849/51 and 1949, shoreline recession was the only trend, with increasing magnitude toward the inlet. The average recession rate between Nags Head and Oregon Inlet was about 1.0 m/yr with maximum retreat rates of about 4 m/yr along southern Bodie Island (Figure 3-7). Northern Pea Island receded approximately 3.5 m/yr for the same period.

3.1.3.2 1949 to 1980

Although four shorelines exist for this period of record, only the 1949 to 1980 change data are continuous from Nags Head to Oregon Inlet. All shorelines were captured from near-vertical aerial photography by the NOS. From 1949 to 1962, the southern 8 to 9 km of Bodie Island were compared. The northern 2 km of beach was slightly accretional, and the southern 6 to 7 km north of Oregon Inlet was receding at an average rate of 7.2 m/yr (peak recession rate about 28 m/yr, Figure 3-8). These accelerated rates of change relative to any other time period reflect the impact of the March 1962 Ash Wednesday Storm (Dolan, 1987). Not only were shoreline recession rates magnified, but the net southerly growth of Bodie Island was temporarily reversed due to severe erosion of beaches adjacent to the inlet. By 1975, the southern 5.5 km of Bodie Island exhibited erosion and accretion trends consistent with long-term changes. The southernmost one km of beach adjacent to the inlet illustrated net advance at a rate of about 5.0 m/yr, and the 4.5-km long beach north of this point receded at an average rate of 5.2 m/yr (Figure 3-9). The beach along northern Pea Island receded at about 2.6 m/yr (maximum recession rate of approximately 16 m/yr).

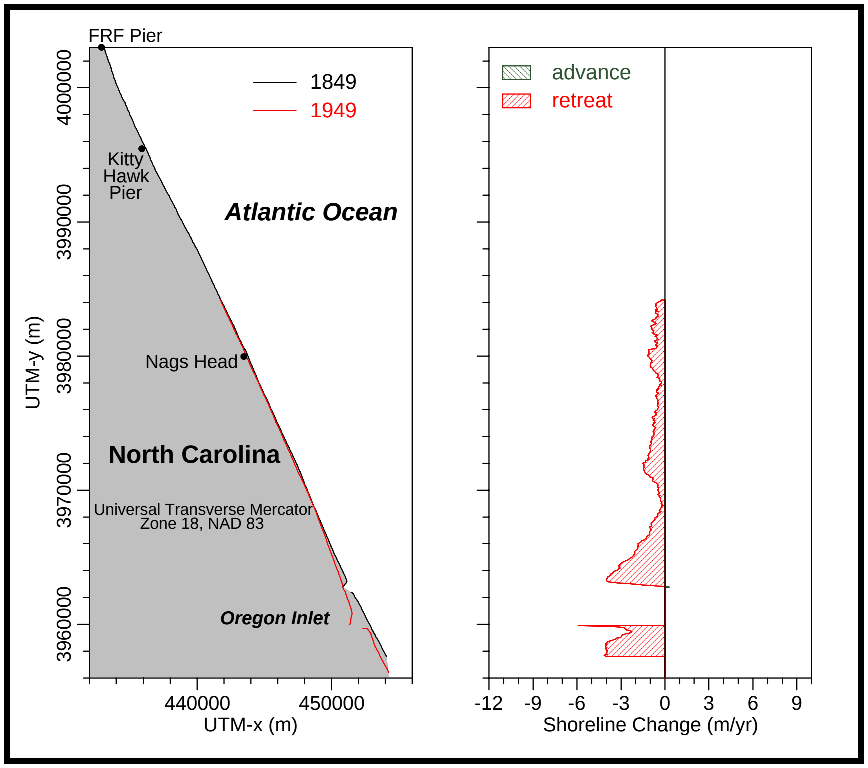

Figure 3-7. Shoreline position and change between the Nags Head and Oregon Inlet, NC, 1849/51 to 1949.

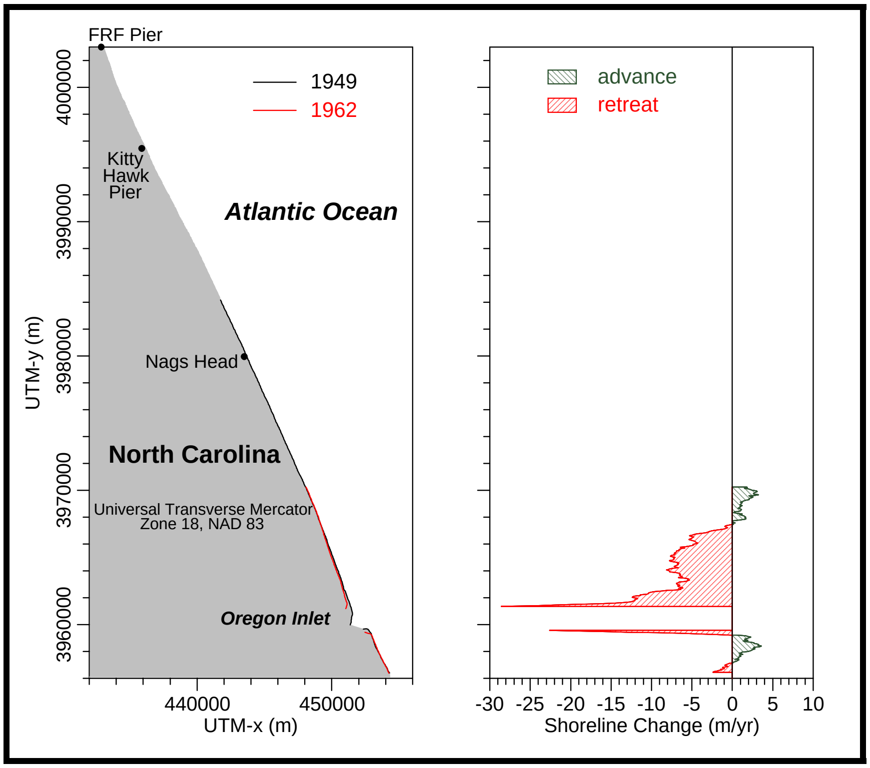

Figure 3-8. Shoreline position and change along southern Bodie Island, NC, 1949 to 1962.

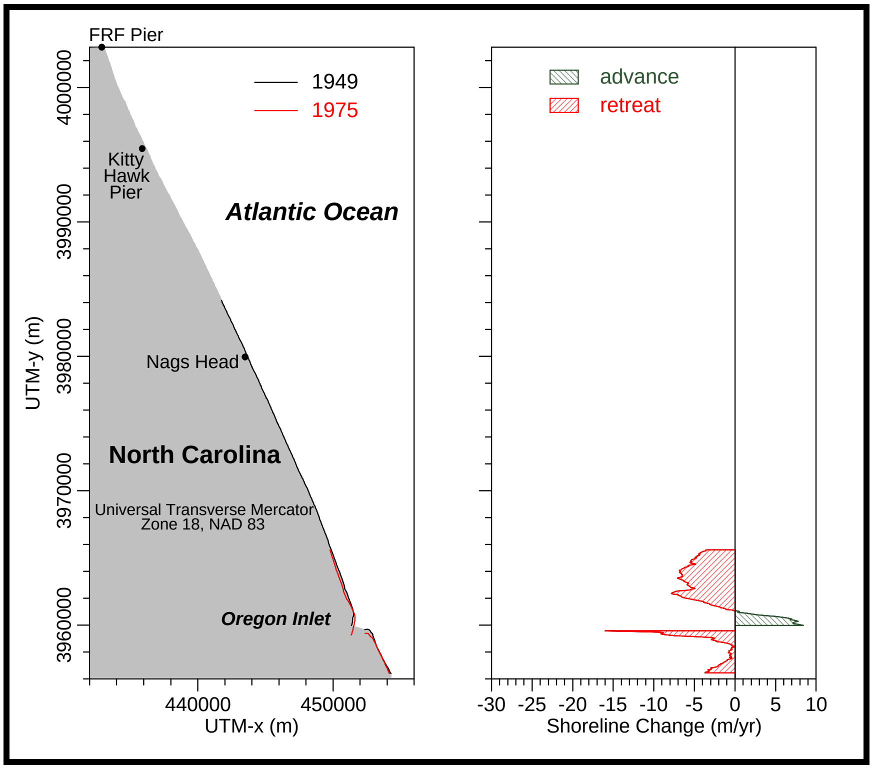

Figure 3-9. Shoreline position and change along southern Bodie Island, NC, 1949 to 1975.

Net shoreline change between 1949 and 1980 documented recession everywhere except along the north beach adjacent to Oregon Inlet. From north of Nags Head to the accretion zone adjacent to Oregon Inlet, shoreline recession averaged 1.8 m/yr. However, the northern 15 km of beach receded at a rate of 0.9 m/yr, and the southern 7 km of the erosion zone receded at about 3.7 m/yr (Figure 3-10). The accretion area adjacent to the inlet extended approximately 1.7 km, and the average rate of shoreline advance was 4.5 m/yr. South of the inlet for 3 km, shoreline recession dominated at an average rate of 4.1 m/yr (maximum change rate was -21 m/yr adjacent to the inlet).

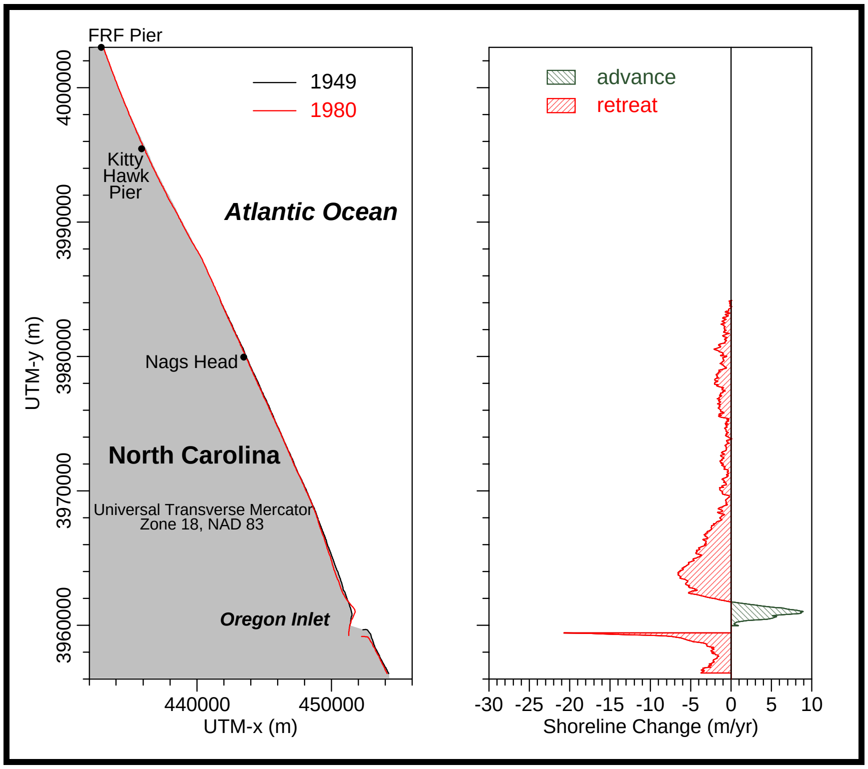

Figure 3-10. Shoreline position and change between the Nags Head and Oregon Inlet, NC, 1949 to 1980.

3.1.3.3 Cumulative Shoreline Position Change (1849/51 to 1980)

Shoreline position change between 1849/51 and 1980 documents persistent shoreline recession along most of the coast between the USACE FRF Pier and northern Pea Island (Figure 3-11). Average shoreline change north of Oregon Inlet was about -0.7 m/yr (σ = ±0.9 m/yr). However, accelerated beach erosion on either side of Oregon Inlet resulted in net inlet migration to the south at about 3.5 km (27.1 m/yr). Shoreline recession along the southern 5.7 km of Bodie Island was about 2.4 m/yr (σ = ±1.2 m/yr), whereas shoreline change north of this area to the FRF Pier averaged -0.5 m/yr (σ = ±0.4 m/yr). Along northern Pea Island, shoreline recession was approximately 3.8 m/yr (σ = ±0.7 m/yr) for the period of record (Figure 3-11). As with all time intervals, greatest shoreline changes were associated with beaches adjacent to Oregon Inlet.

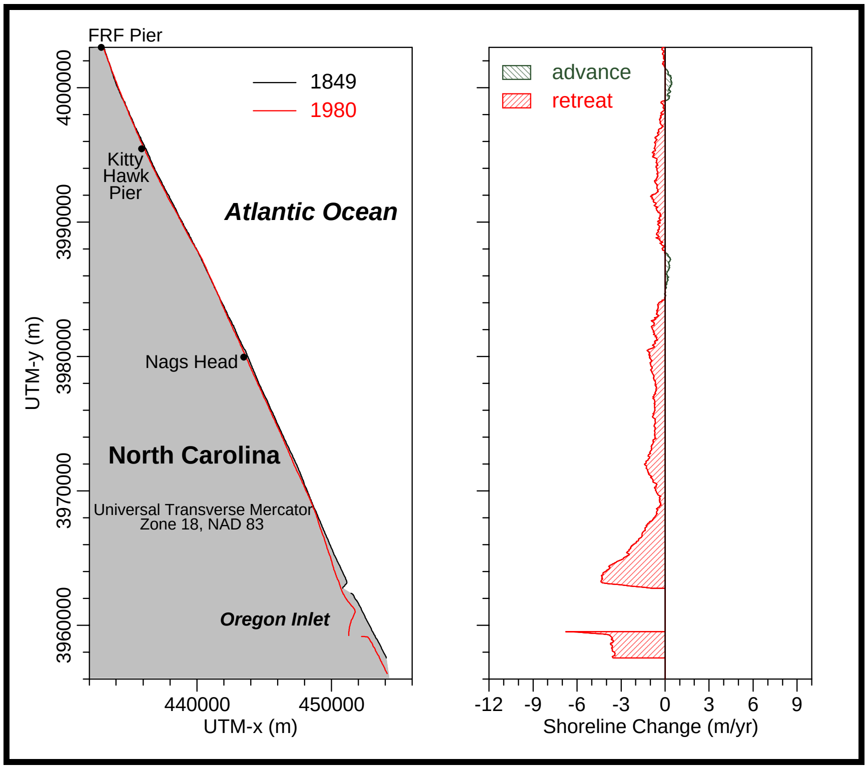

Figure 3-11. Shoreline position and change between the FRF Pier and northern Pea Island, just south of Oregon Inlet, NC, 1849/51 to 1980.

3.2 NEARSHORE BATHYMETRY CHANGE

3.2.1 Bathymetry Data Base and Potential Errors

Seafloor elevation measurements collected during historical hydrographic surveys are used to identify changes in nearshore bathymetry for quantifying sediment transport trends relative to natural processes and engineering activities. Two USC&GS bathymetry data sets were used to document seafloor changes between 1862/70 and 1970/75. In addition, nearshore bathymetry data collected by the USACE, Wilmington District, in 1996 between Oregon Inlet and Kitty Hawk supplemented the 1970/75 USC&GS data. Temporal comparisons were made for about 50 km of coast from 10 km north of Kitty Hawk to 3 km south of Oregon Inlet. Data extended offshore to about the 30-m depth contour (about 15 km offshore). The survey sets consist of digital data compiled by the National Geophysical Data Center (NGDC) and analog information (maps) that were compiled using standard digitizing procedures (see Byrnes and Hiland, 1994).

The first regional USC&GS bathymetric survey was conducted in 1862/70 (Table 3-4); data were registered in units of feet. The survey of Oregon Inlet in 1862 was conducted at a scale of 1:10,000, whereas offshore surveys (1868 and 1870) focused on regional data coverage at a scale of 1:40,000. The density of points was reasonable for characterizing coastal and shelf topography; however, the most recent survey (1970/75/96) recorded many more points for describing surface characteristics for the same area. The 1862/70 offshore surveys contained an adequate number of depths along each survey line, and longshore spacing of lines was about 0.5 to 1 km. As such, depth values are reasonable for describing

Table 3-4. Summary of bathymetric source data characteristics for the offshore area between Duck and Oregon Inlet, NC.

Date	Data Source	Comments and Map Numbers
1862/70	USC&GS Hydrographic Sheets 1:10,000 (H-762) 1:40,000 (H-965, H-1053)	First regional bathymetric survey for offshore New Jersey; 1862 - first survey of Oregon Inlet; 1868 - offshore area from Duck to south of Kitty Hawk (H-965); 1870 - offshore area from north of Nags Head to Pea Island (H-1053).
1970/75	USC&GS Hydrographic Sheets 1:5,000 (H-9527, H-9529, H-9530) 1:10,000 (H-9525) 1:40,000 (H-9137, H-9525, H-9171)	Most recent offshore regional bathymetric survey; 1970 - offshore Kitty Hawk (H-9171), offshore Nags Head and Oregon Inlet (H-9155), Offshore Pea Island (H-9171); 1975 - Oregon Inlet surveys (H-9525, H-9527, H-9529, H-9530).
1996	U.S. Army Corps of Engineers digital bathymetric survey	Along the beaches and in the nearshore off Dare County, NC between Kitty Hawk and Oregon Inlet.

bathymetric features and compared well with the 1970/75/96 survey set. The 1970/75 bathymetric data are available in digital format from the NGDC, and the 1996 data area available from the USACE, Wilmington District.

As with shoreline data, measurements of seafloor elevation contain inherent uncertainties associated with data acquisition and compilation. Potential error sources for horizontal location of points are identical to those for shoreline surveys (see Table 3-2). These shifts in horizontal position translate to vertical adjustments of about ±0.3 to 0.5 m based on information presented in USC&GS and USACE hydrographic manuals (e.g., Adams, 1942). Corrections to soundings for tides and sea level change introduce additional errors in vertical position of ±0.1 to 0.3 m. Finally, the accuracy of the depth measurement adds uncertainty that is variable depending on the measurement method. Using this information, it is estimated that the combined root-mean-square error for bathymetric surface comparison between 1862/70 and 1970/75/96 is about ±0.6 m. This estimate was used to denote areas of no significant change on surface comparison maps.

Because seafloor elevations are temporally and spatially inconsistent for the entire data set, adjustments to depth measurements were made to bring all data to a common point of reference. These corrections include changes in relative sea level with time and differences in reference vertical datums. Vertical adjustments were made to each data set based on the time of data collection. All depths were adjusted to NGVD and projected average sea level for 1980. The unit of measure for all surfaces is meters, and final values were rounded to one decimal place before cut and fill computations were made.

3.2.2 Digital Surface Models

Historical bathymetry data within the study area provide geomorphic information on characteristic surface features that form in response to dominant coastal processes (waves and currents) and relative sea level change. Comparing two or more surfaces documents net sediment transport patterns relative to incident processes and sediment supply. The purpose of conducting this analysis throughout the study area is to document net sediment transport trends on the shelf surface and to quantify the magnitude of change to calibrate the significance of short-term wave and sediment transport numerical modeling results. Net sediment transport rates on the shelf were determined using historical data sets to address potential infilling rates for sand borrow sites.

3.2.2.1 1862/68/70 Bathymetric Surface

Bathymetry data for the period 1862/68/70 were combined with the 1849/51 shoreline data to create a continuous surface from the shoreline seaward to about the 25- to 30-m depth contour (NGVD). The most prominent geomorphic features throughout the study area are the linear offshore sand ridges north and south of Oregon Inlet (Figure 3-12). Because of data density limitations, these features are not as well defined as for the 1970/75/96 bathymetric surface. However, the presence of large N-S oriented ridges landward and seaward of the Federal-State OCS boundary is represented in the data set as a primary offshore sand source for beach nourishment. The characteristics of these shoal features are best defined north of Oregon Inlet for an area known as Platt Shoals. The origin of sand ridges has been associated with lateral inlet migration along a landward migrating shoreline (McBride and Moslow, 1991), suggesting that sediment associated with offshore sand ridges is compatible with modern beach deposits. Historical shoreline change data illustrate substantial lateral island migration and shoreline retreat between 1849/51 and 1980, providing a mechanism for oblique sand ridge formation on the shoreface. Geological data from the NCGS (Boss and Hoffman, 2001) illustrate that shoreface sand ridges are the most viable features for beach sand on the continental shelf in this area. Southward migration of southern Bodie Island indicates dominant southward-directed longshore transport within 5 to 10 km of the inlet (see Figure 3-11), and the predominance of shallow shoals on the north side of Oregon Inlet supports this conclusion.

3.2.2.2 1970/75/96 Bathymetric Surface

General characteristics of the 1970/75/96 bathymetric surface are similar to those of the 1862/68/70 surface with a couple of exceptions (Figure 3-13). First, the area of coverage extends much farther offshore the study area. Second, geomorphic features are better defined because the number of data points describing the surface is larger. The general shape and position of shoals is consistent for both surfaces. However, the detail associated with shoals along the coast and linear sand ridges on the shoreface provides an understanding of the relationship between potential sand borrow sites and coastal sedimentation processes. All potential sand borrow sites exist on offshore N-S oriented sand ridges, which have been linked with ancient inlet deposits during lower sea level (McBride and Moslow, 1991).

The shelf surface seaward of Oregon Inlet illustrates the influence of tidal inlet sedimentation processes on shelf morphology. The delta-shaped bulge in contours, marked by the 10-m depth contour, documents the longshore extent (about 5 km) of inlet-influenced sedimentation on shelf morphology. Although the tidal prism associated with this inlet is relatively large, ocean wave processes exert substantial influence on sediment transport patterns, creating ebb shoals in close proximity to the coast and an extensive flood shoal complex (Figure 3-14). Inlet shoals are composed primarily of sand contributed by longshore transport from adjacent beaches, so the genetic link between offshore sand ridges and the migration of inlets and beaches emphasizes the importance of shoal features as a viable source of sand for beach nourishment and coastal restoration.

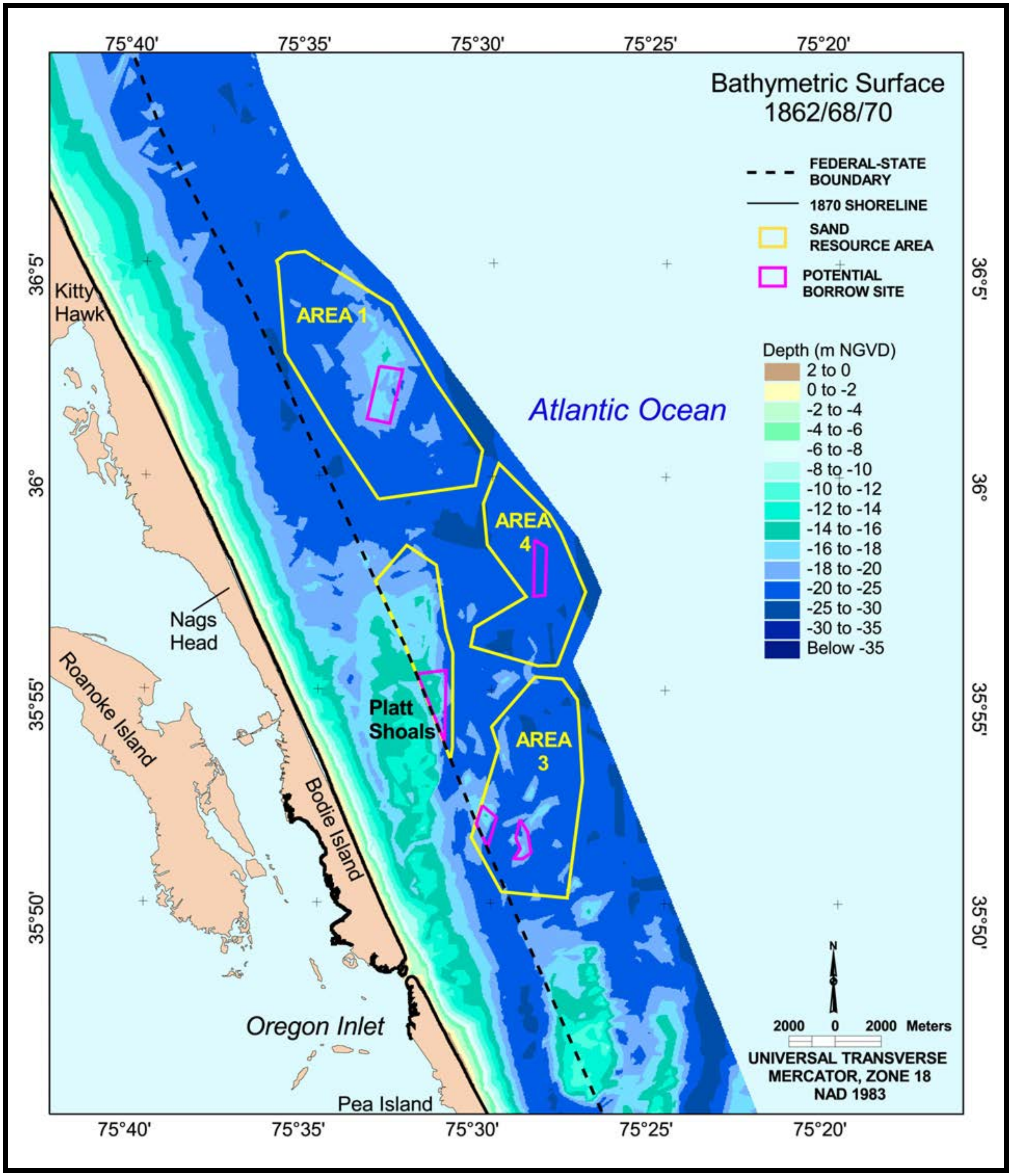

Figure 3-12. Nearshore bathymetry (1862/68/70) for offshore Dare County, NC.

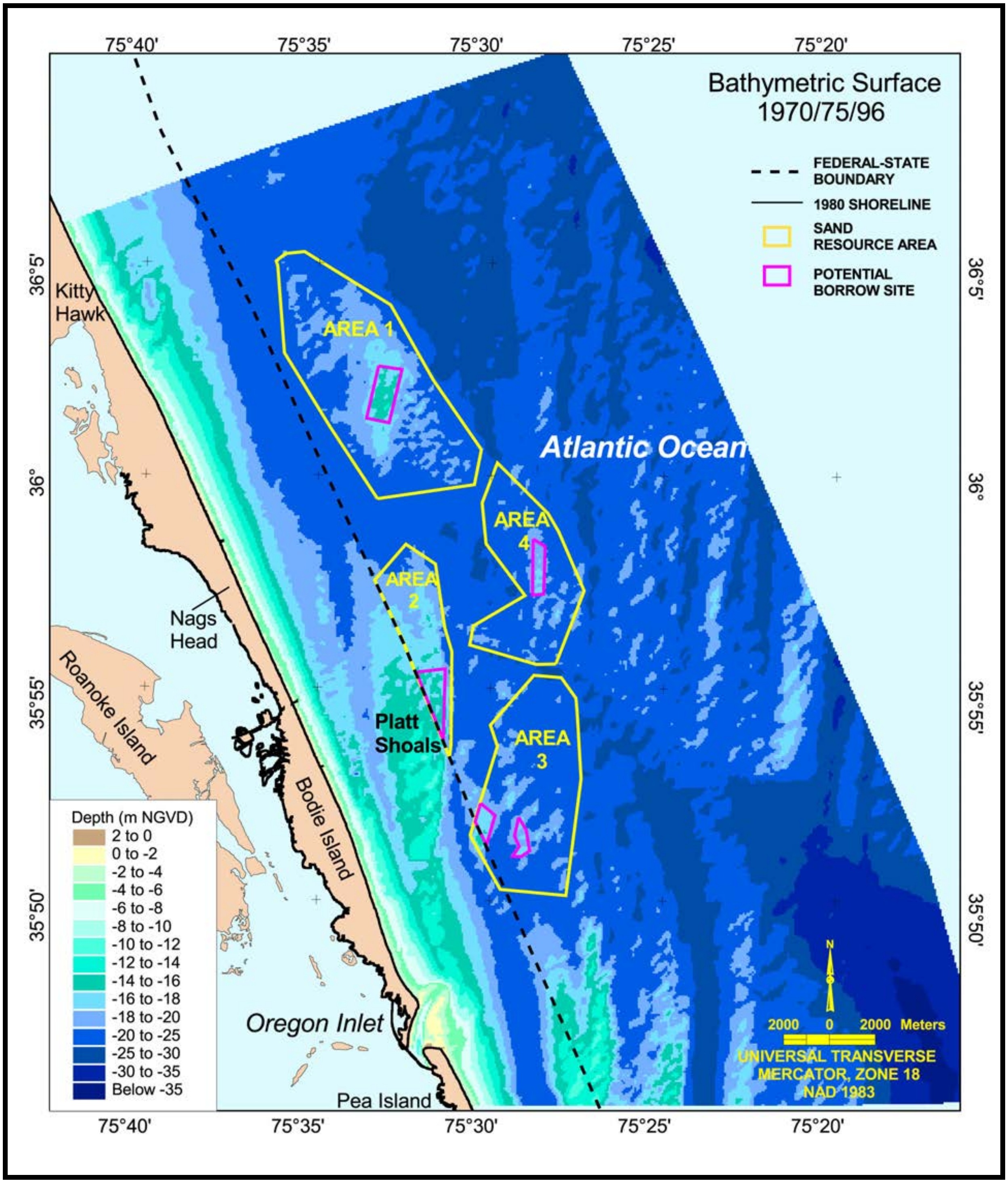

Figure 3-13. Nearshore bathymetry (1970/75/96) for offshore Dare County, NC.

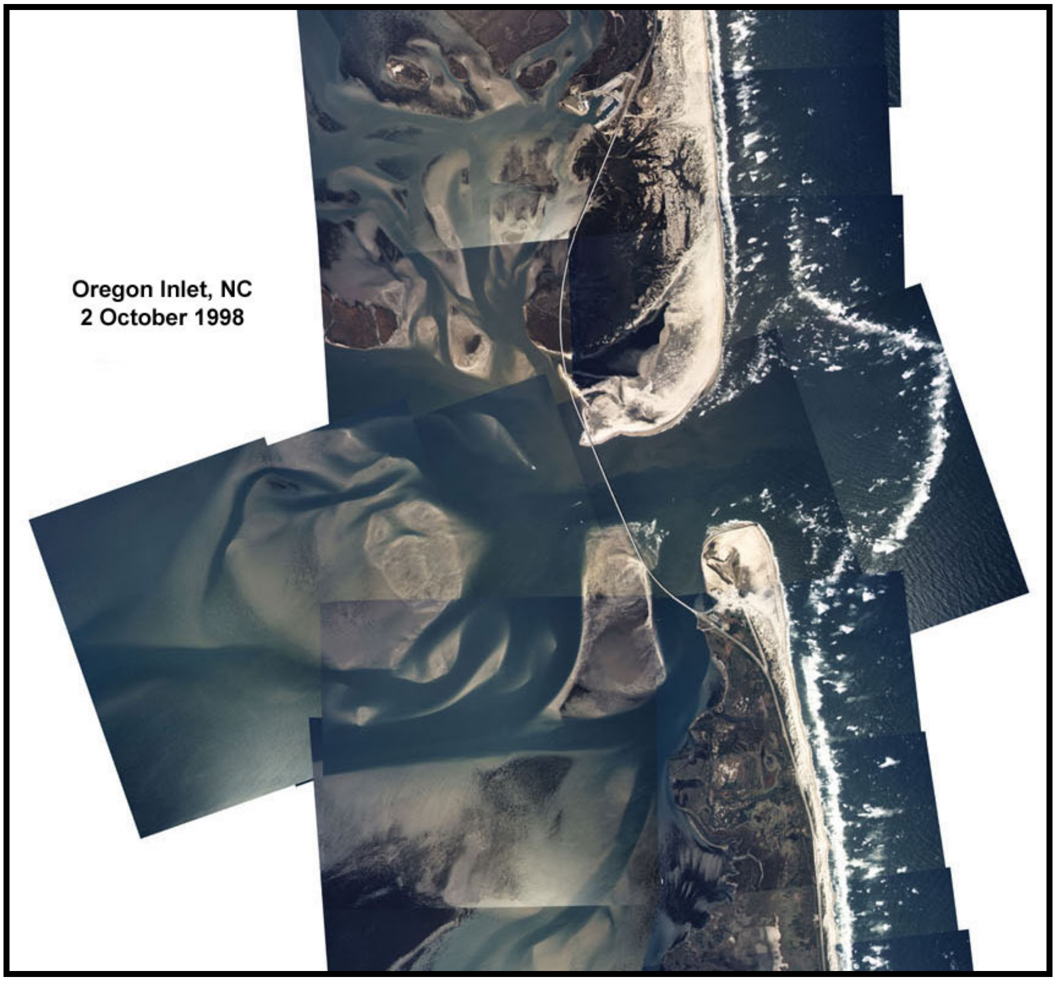

Figure 3-14. Aerial photograph of Oregon Inlet illustrating the extent of ebb and flood shoal development.

3.2.3 Shelf Sediment Transport Dynamics

Although the general characteristics of bathymetric surfaces appear similar for 1862/68/70 and 1970/75/96, a digital comparison of these surfaces yields a difference plot that isolates areas of erosion and accretion for documenting sediment transport patterns and quantifying trends (Figure 3-15). The most significant changes occurring during this 100-yr interval were associated with deposition (and erosion) at and seaward of Oregon Inlet, along the beaches of Dare County, and associated with the movement of offshore sand shoals throughout the study area. Tidal exchange through Oregon Inlet mobilizes substantial quantities of sediment near the coastline and on the upper shoreface, resulting in spit growth along the downdrift margin of Bodie Island and shoal migration at and adjacent to the entrance, illustrated as areas of erosion (yellow to brown) and deposition (blue to green) on Figure 3-15. Without exception, beach and nearshore regions from Kitty Hawk to Pea Island are net erosional. On the shoreface, sediment transport patterns at sand ridges (e.g., Platt Shoals) illustrate net migration to the south-southeast since 1868/70. The magnitude of erosion and deposition indicates an active shelf surface in response to storm and normal wave and current processes. A general pattern of alternating zones of accretion and erosion reflect the net southward migration of continental shelf sand ridges.

Prominent zones of sediment deposition (green) seaward of the eroding beach and upper shoreface (orange and brown) are persistent throughout the study area. These zones of sediment accretion are associated with south-southeast directed shoal migration and development and migration of the ebb-tidal shoal at Oregon Inlet. Often, updrift zones of erosion are associated with downdrift linear deposits, illustrating the historical movement of shoals on the shelf surface. The greatest amount of bathymetric change on the shelf surface is associated with sand resource areas and the development of an ebb shoal seaward of Oregon Inlet. Sand volume change calculations for zones of accretion and erosion along the shore and on the shelf surface are used to estimate net sand transport rates (see Sections 3.2.4 and 3.2.5). Historical transport rates are used to calibrate simulations of borrow site infilling and nearshore sand transport (Section 5.2).

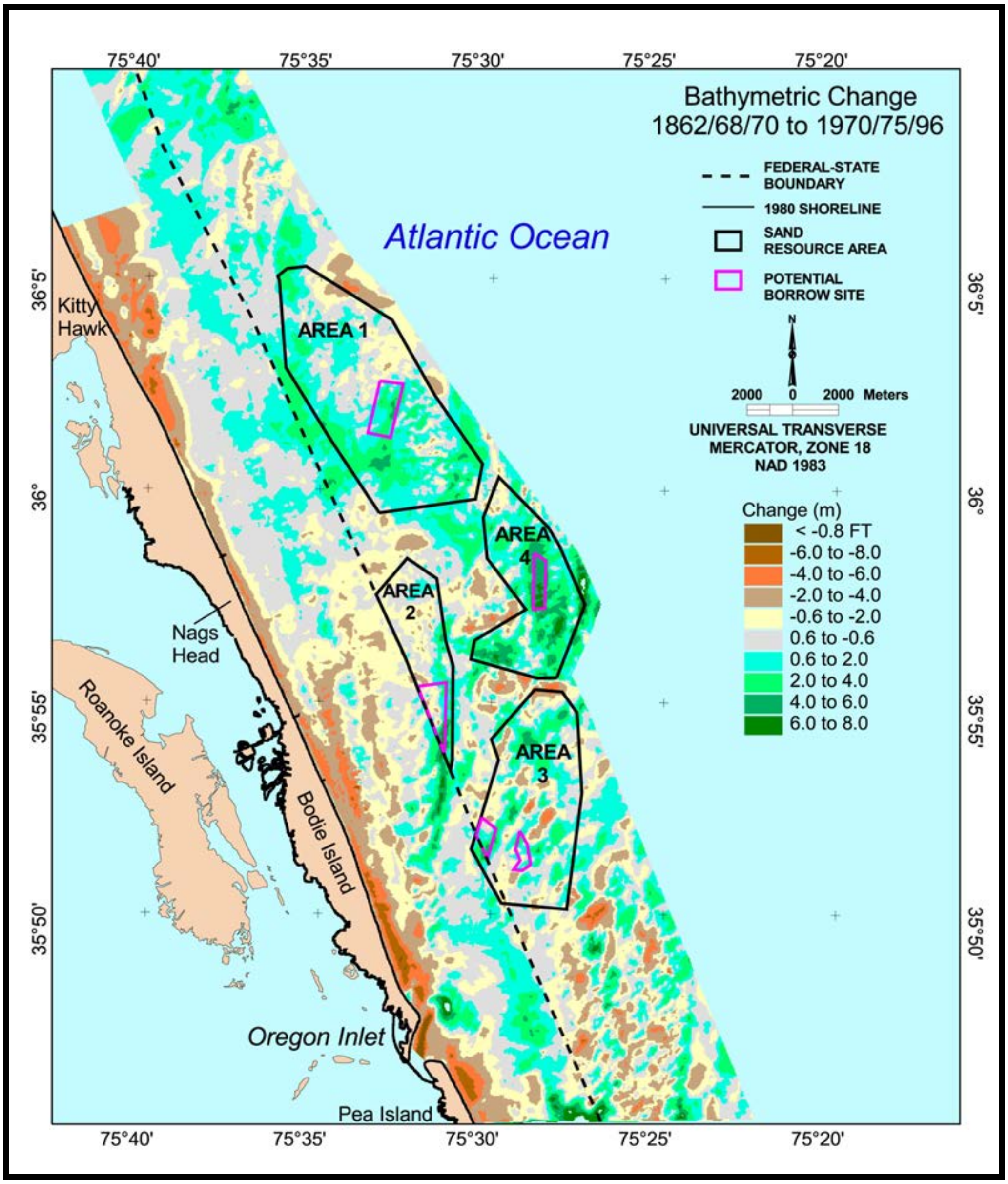

Figure 3-15. Nearshore bathymetry change (1862/68/70 to 1970/75/96) for offshore Dare County, NC.

3.2.4 Magnitude and Direction of Change

Patterns of seafloor erosion and accretion on the continental shelf from Kitty Hawk to Pea Island, NC documented the net direction of sediment transport throughout the study area (Figure 3-15). For the period 1862/68/70 to 1970/75/96, net sediment movement on the continental shelf is to the south. This direction of transport is consistent with historical shoreline change trends near Oregon Inlet. Although overall trends are helpful for assessing potential impacts of sand extraction from the OCS, the specific purpose of historical bathymetry change assessment is to quantify sediment erosion and accretion and to derive net transport rates specifically related to potential sand extraction sites. For the four potential sand resource areas, five borrow sites were identified for evaluating sand extraction scenarios based on discussions of beach replenishment needs with USACE, Wilmington District, and MMS personnel.

For Sand Resource Area 1, variations in sediment deposition over and adjacent to the proposed borrow site were evaluated for two locations, each equal to the area of the proposed borrow site. Potential transport rates available for infilling a proposed sand borrow site of this size would range from about 53,000 to 68,000 m^3/yr (6.9 to 8.9 MCM over about 100 years; Figure 3-16). This calculation assumes that sediment deposited in areas adjacent to potential borrow sites reflects the rate at which material would be available for infilling the borrow sites. For Areas 2 through 4, similar calculation procedures were applied to develop a range of potential infilling rates for each borrow site. Potential infilling rates at the borrow site in Area 2 range from 39,000 to 70,000 m^3/yr, whereas to the south and east of this site in Area 3, potential infilling rates ranged from 20,000 to 27,000 m^3/yr. At Area 4, potential infilling rates ranged from 36,000 to 45,000 m^3/yr. Overall, potential infilling rates derived from 100-yr historical deposition trends on the shelf surface adjacent to each of the sand borrow sites are relatively consistent. However, dredging geometry for each potential borrow site (depth to width to length), as well as the type of sediment available for infilling, are controlling factors for determining sediment infilling (see Section 5.2).

Table 3-5 summarizes potential extraction and infilling characteristics for each of the borrow sites. Although Area 4 is farthest offshore, the average time it would take to fill this site (based on 100-yr sedimentation trends) after mining all available sand would be about 57 years. Conversely, areas with the greatest amount of sand for beach nourishment (1 and 2) would take longest to fill if the entire volume were extracted. For a single fill of 2 MCM, the borrow sites in Areas 1 and 2 would refill in about 30 to 35 years. Infilling times would be about two times greater for the other borrow sites.

Table 3-5. Sand volume extraction from potential borrow sites relative to computed infilling rates.

Sand Borrow Site	Borrow Site Sand Volume (MCM)	Excavation Depth (m)	D50 (mm)	Infilling Rate (m^3/yr)		Average Infilling Time (years)
				Low	High	
1	7.2	3	0.41	53,000	68,000	119
2	5.8	3	0.50	39,000	70,000	106
3 east	1.4	2	0.21	20,000	23,000	65
3 west	2.5	3	0.27	24,000	27,000	98
4	2.3	2	0.36	36,000	45,000	57

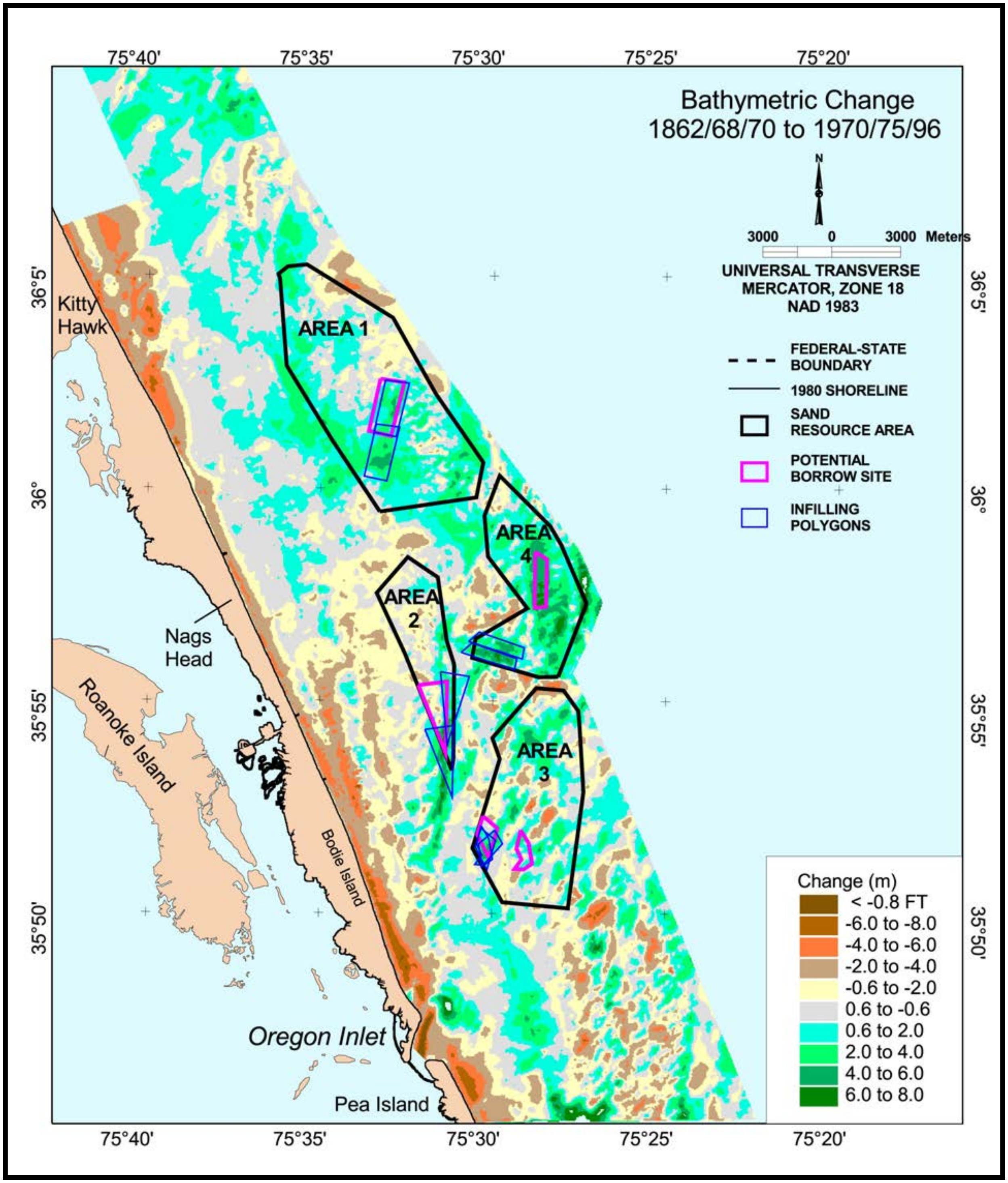

Figure 3-16. Polygon geometry and locations used for estimating infilling rates (blue) relative to sand borrow site locations offshore North Carolina.

3.2.5 Net Longshore Sand Transport Rates

A continuous zone of erosion along the shoreline is documented in Figure 3-16 as characteristic of littoral sand transport along the beaches in Dare County, NC. The littoral zone extends seaward to about the 10-m (NGVD) depth contour, which represents the approximate depth of closure (determined from geomorphic characteristics of the change surface [Figure 3-15], profiles change analyses by Larson and Kraus [1994], and based on calculations of d_l from Hallermeier [1981] using USACE Wave Information Study [WIS] data statistics). Net longshore sand transport rates were determined between Kitty Hawk and Oregon Inlet by quantifying variations in beach erosion, as determined from historical bathymetry comparisons, in a sediment budget context. In Section 4.2.2.1, the distribution of longshore sediment transport potential was computed throughout the study area. A transport reversal was identified about 10 km north of Oregon Inlet. With this information (Q = 0 about 10 km north of the inlet) and erosion quantities for 3 km shoreline segments along the coast, a sediment budget was developed to document variations in net transport rates. North of the nodal point, beach and nearshore erosion varied from 50,000 to 110,000 m^3/yr. South of the nodal point, erosion rates varied from 75,000 to 170,000 m^3/yr. Assuming about 25,000 m^3/yr is transported offshore, net transport rates are about 160,000 m^3/yr near Nags Head and about 335,000 m^3/yr near Kitty Hawk. These numbers are very consistent with those computed in Figure 4-17. In the same manner, south-directed transport adjacent to Oregon Inlet is about 354,000 m^3/yr.

3.3 SUMMARY

Shoreline position and nearshore bathymetry change document four important trends relative to study objectives. First, the predominant direction of sediment transport on the continental shelf and along southern Bodie Island is north to south. However, littoral transport between Kitty Hawk and a point about 10 km north of Oregon Inlet is to the north. The greatest amount of shoreline change was associated with beaches adjacent to Oregon Inlet (-2 to -6 m/yr along southern Bodie Island); since 1849/51, southern Bodie Island has grown to the south at a rate of about 27 m/yr. Second, the most dynamic features within the study area are the beaches and shoals associated with Oregon Inlet. Areas of significant erosion and accretion are documented for the period 1862/68/70 to 1970/75/96, reflecting wave and current dynamics near the entrance and the contribution of littoral sand transport from the north to channel, shoal, and spit migration.

Third, alternating bands of erosion and accretion on the continental shelf east of Federal-State boundary illustrate relatively slow but steady reworking of the upper shelf surface as sand ridges migrate from north to south. The process by which this is occurring at all resource areas suggests that borrow sites in these regions would fill with sand transported from the adjacent seafloor at rates ranging from 20,000 to 70,000 m^3/yr. For a 2 MCM sand extraction scenario, infilling times for borrow sites in Areas 1 and 2 would be about 30 to 35 years.

Finally, net longshore transport rates determined from seafloor changes in the littoral zone between Kitty Hawk and Oregon Inlet and nodal point information derived in Section 4.2.2.1 indicate increasing transport rates north and south of a point about 10 km north of the inlet. Net longshore transport near Nags Head was about 160,000 m^3/yr to the north, increasing to about 335,000 m^3/yr near Kitty Hawk. These rates are very consistent with those determined from wave and sediment transport modeling. Just north of Oregon Inlet, net transport rates were determined to be about 354,000 m^3/yr.

4.0 WAVE TRANSFORMATION NUMERICAL MODELING AND NEARSHORE SEDIMENT TRANSPORT

Excavation of a borrow site in the nearshore can affect wave heights and the direction of wave propagation. An offshore "hole" or "trench" can cause waves to refract toward the shallower edges of the borrow site. This alteration to the wave field by a borrow area may change local sediment transport rates, where some areas may experience a reduction in longshore transport, while other areas may show an increase. To determine potential physical impacts associated with dredging of a borrow site located offshore North Carolina in the vicinity of Bodie Island, wave transformation modeling and sediment transport potential calculations were performed for existing and post-dredging bathymetric conditions. Comparison of computations for existing and post-dredging conditions illustrated the relative impact of borrow site excavation on wave-induced coastal processes.

The most effective means of quantifying physical environmental effects of sand dredging from shoals on the continental shelf is through use of wave transformation numerical modeling tools that recognize the random nature of incident waves as they propagate onshore. Spectral wave models, such as STWAVE (STeady-state spectral WAVE model), REF/DIF-S (REFraction/DIFfraction model for Spectral wave conditions), SWAN (Simulation of WAves Nearshore), and others, typically provide more realistic results than monochromatic wave models relative to field measurements. As such, spectral wave transformation modeling was applied in this study to evaluate potential impacts to coastal and nearshore sites from long-term dredging and significant removal of sand from offshore sand borrow sites. Although interpretation of wave modeling results is relatively straightforward, evaluating the significance of predicted changes for accepting or rejecting a borrow site is more complicated.

As part of any offshore sand mining effort, the MMS requires evaluation of potential environmental impacts associated with alterations to nearshore wave patterns. To determine potential impacts associated with borrow site excavation, the influence of borrow site geometry on local wave refraction patterns is evaluated. Because large natural spatial and temporal variability exists within the wave climate at a particular site, determination of physical impacts associated with sand mining must consider the influence of process variability. A method based on historical wave climate variability, as well as local wave climate changes directly attributable to borrow site excavation, has been applied to determine appropriate criteria for assessing impact significance.

To directly assess impacts to coastal processes associated with sand mining, an approach has been utilized that considers spatial (longshore) and temporal aspects of the local wave climate, as described in Kelley et al. (2001). For this study, this method was applied by performing wave model runs using mean conditions developed using the entire 20-year WIS record to develop average conditions, and then 20 year-long blocks of the WIS record to determine annual variability of the wave climate along this shoreline. In this manner, temporal variations in wave climate are considered relative to average annual conditions. From these wave model runs, sediment transport potential curves are derived for average annual conditions (based on the full 20-year WIS record) and each one-year period (based on the 20 one-year wave records parsed from the full record). Applying this information, the average and standard deviation in calculated longshore sediment transport potential is determined every 200 m along the shoreline.

Assuming the temporal component of sediment transport potential is normally distributed, the suggested criterion for accepting or rejecting a potential borrow site is based on a range of one standard deviation about the mean. As proposed, the criteria would require that if any portion of the sediment transport potential curve associated with a sand mining project exceeds one-half of a standard deviation of the natural temporal variability (which incorporates 1/3 of the variability) in sediment transport potential, the site would be rejected, or accepted conditionally. Conversely, a borrow site design would be accepted unconditionally as long as the transport potential change determined for post-dredging conditions at a site falls within the range of one-half of a standard deviation.

Conditional acceptance of a borrow site design could be allowed for sites that change transport potential between one-half and one standard deviation at any point along a shoreline. This conditional acceptance would require either mitigation along the affected shoreline, which would likely be in the form of an appropriately sized beach nourishment, or a redesign of the proposed borrow site configuration to reduce impacts to within acceptable limits. If borrow site dredging impacts transport potential in excess of one standard deviation, the impact is considered too great for mitigation, and therefore the site must be either rejected or redesigned to reduce impacts to within acceptable limits. This methodology provides a useful indication of sediment transport variability relative to the natural system.

An example of this method taken from previous work (Kelley et al., 2001) is shown in Figure 4-1, where alterations in wave climate caused by dredging of Sandbridge Shoal, Virginia were determined to be not significant relative to natural variability. The maximum variation in sediment transport potential caused by dredging Sandbridge Shoal was determined to be approximately 25,000 m^3 per year, where the standard deviation of the natural sediment transport variability was approximately 100,000 m^3/yr. Due to the relatively high natural variability in wave climate in this area, an observer on the shoreline is unlikely to notice alterations in shoreline position caused by borrow site dredging. For this reason, sites with large natural variation in wave climate and associated sediment transport potential would be allowed to have larger impacts associated with an offshore sand mining project.

As a management tool for the MMS, this methodology provides several advantages over methods previously used to assess the significance of borrow site impacts. The primary advantages include:

1. Observed long-term shoreline change is compared with computed longshore change in sediment transport potential. Close comparison between these two curves indicates that longshore sediment transport potential calculations are appropriate for assessing long-term natural change. Therefore, this methodology has a model-independent component (observed shoreline change) used to ground truth the model results.

2. The method is directly related to sediment transport potential and associated shoreline change. Therefore, impacts associated with borrow site excavation can be directly related to their potential influence on observed coastal processes (annualized variability in shoreline position).

3. Site-specific temporal variability in wave climate and sediment transport potential is calculated as part of the methodology. For sites that show little natural variability in inter-annual wave climate, allowable coastal processes impacts associated with borrow site dredging similarly would be limited, and *vice versa*. In this manner, the inter-annual temporal component of the natural wave climate is a major component in the determination of impact significance.

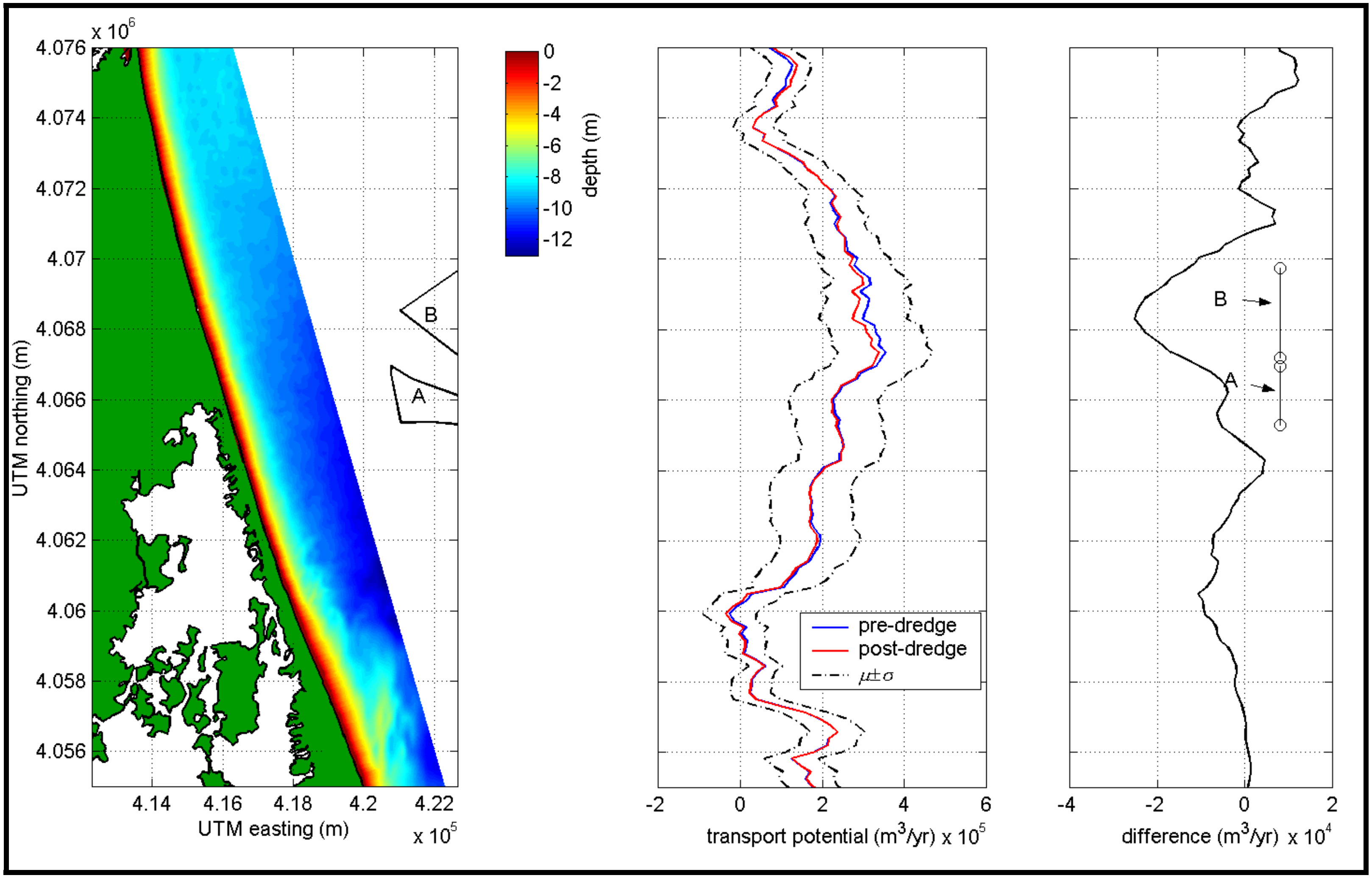

Figure 4-1. Example of results for spatial/temporal variability method for determining significance of borrow site dredging impacts (Kelley et al., 2001). Plots of modeled net transport potential and post-dredging change in transport for borrow sites located offshore Sandbridge, Virginia. Middle plot shows dredging significance criterion envelope ($\pm\sigma$) determined for this shoreline. The left plot of the shoreline is given for reference.

4. Similar to methodologies incorporated in previous MMS studies, the longshore spatial distribution of borrow site impacts is considered. However, the allowable limit of longshore sediment transport variability is computed from the temporal component of the analysis. Therefore, the final results of this analysis provide a spatially-varying envelope of allowable impacts in addition to the modeled impacts directly associated with borrow site excavation. The methodology accounts for spatial and temporal variability in wave climate, as well as providing a defensible means of assessing significance of impacts relative to site-specific conditions.

4.1 ANALYSIS APPROACH

Sediment transport rates along a coastline are dependent on wave climate in that area. For this study, nearshore wave heights and directions along the shoreline landward of the proposed borrow sites were estimated using the USACE spectral wave model STWAVE, which is used to simulate propagation of offshore waves to the shoreline. Offshore wave data, available from the WIS were used to derive input wave conditions for STWAVE.

4.1.1 Wave Modeling

Developed by the USACE Waterways Experiment Station (WES), STWAVE v2.0 is a steady state, spectral wave transformation model (Smith et al., 1999). Two-dimensional (frequency and direction vs. energy) spectra are 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 period T_p, and mean wave direction $\bar{\theta}$.

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. This is why 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. As such, the changing wave spectra across each grid column are in turn computed using information solely from the previous grid column.

STWAVE is based on a form of the wave action balance equation. For this model, 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 of wave orthogonal, wave ray, and current directions is shown in Figure 4-2. The governing equation of wave transformation, using the action balance spectrum, in tensor notation is written as (Smith et al., 1999)

$$\left(C_{ga}\right)_i \frac{\partial}{\partial x_i} \frac{C_a C_{ga} \cos(\mu-\alpha) E}{\omega_r} = \sum \frac{S}{\omega_r} \tag{4.1}$$

where

$E = E(f,\theta)$ wave energy density spectrum,
S = energy source and sink terms (e.g., whitecapping, breaking, wind input),
α = wave orthogonal direction,

μ = wave ray direction (direction of energy propagation),
ω_r = relative angular frequency ($2\pi f_r$),
C_a, C_{ga} = absolute wave celerity and group celerity, respectively.

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

$$H_{mo(max)} = 0.1L \tanh (kd) \tag{4.2}$$

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

$$H_{mo(max)} = 0.64\, d \tag{4.3}$$

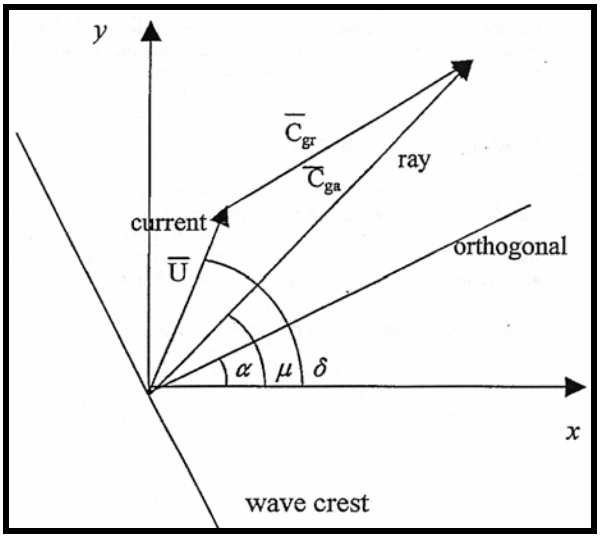

Figure 4-2. Diagram of wave and current vectors used in STWAVE. Subscript *a* denotes values in the *absolute* frame of reference, and subscript *r* denotes values in the *relative* frame of reference (with currents).

An advantage of using Equation 4.2 over Equation 4.3 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, essentially 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, non-linear transfers of energy to high frequencies during breaking are not included in STWAVE.

4.1.1.1 Input Spectra Development

Wave input conditions for simulations offshore North Carolina were developed using hindcast data from WIS Station AU2056 (Figure 4-3), which is located approximately 33 km northeast of Bodie Island, NC. This WIS record covers a 20-year period from January 1976 to

December 1995. Two wave roses showing percent occurrence of different wave conditions are shown in Figure 4-4. The first rose shows how wave height distribution varies with direction. Most waves (52%) in the WIS record fall within the compass sector between 60° and 120°. The dominant wave direction is east-northeast, from which 32% of waves in the record propagate. The mean height for all waves in the record is 1.5 m, with a standard deviation of 0.9 m. The mean height for waves along the dominant wave direction is 1.2 m, with a standard deviation of 0.8 m. The second rose in Figure 4-4 shows the distribution of peak periods in the record. A significant number of wave events (32%) have peak periods greater than 9 sec, and the mean peak period for the entire record is 8.3 sec.

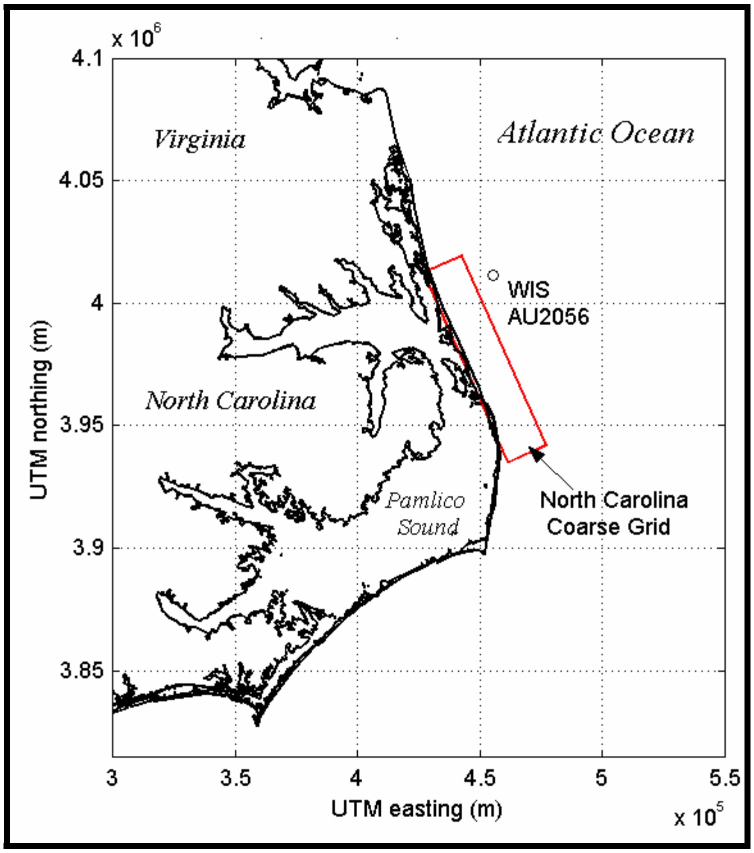

Figure 4-3. Shoreline of southern Virginia and North Carolina with coarse grid limits and WIS wave input data station used to determine dredging impacts from offshore sand mining.

To reduce the offshore extent of the computational grid used by STWAVE, the program WAVETRAN was used to propagate WIS waves closer to shore, from a 37 m (MLLW) water depth at the WIS station, to a 24 m (MLLW) water depth approximately 17 km offshore (the seaward limit of the STWAVE grid). A wave rose of the transformed WIS record is shown in Figure 4-5. WAVETRAN is part of the Shoreline Modeling System (SMS) developed by WES (Jensen, 1983). Because bathymetric contours at these depths generally are oriented north to south offshore Oregon Inlet and Bodie Island, a shoreline orientation of 0° was used as an input to WAVETRAN.

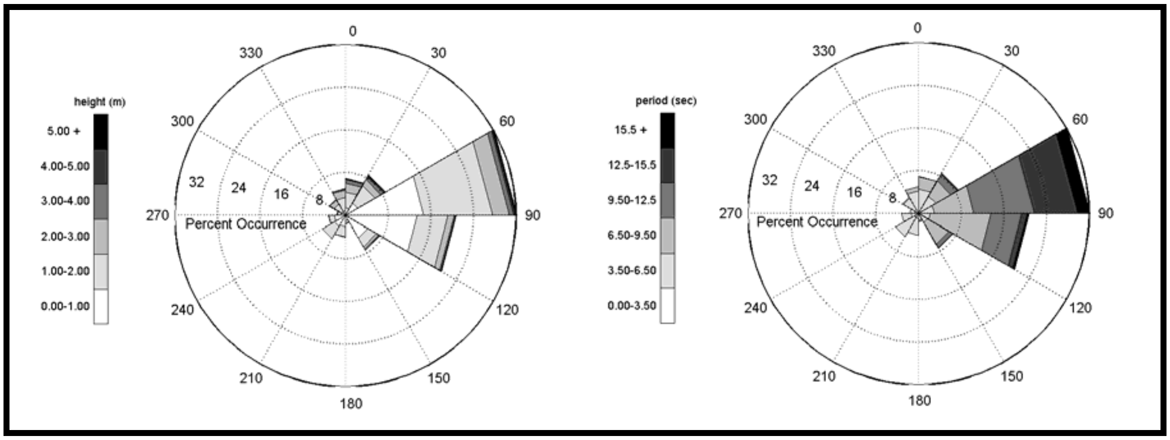

Figure 4-4. Wave height and period roses for hindcast data from WIS Station AU2056 for the 20-year period between January 1976 and December 1995. Direction indicates from where waves were traveling, relative to true north. Radial length of gray tone segments indicate percent occurrence of each range of wave heights and periods. Combined length of segments in each sector indicate percent occurrence of all waves from that direction.

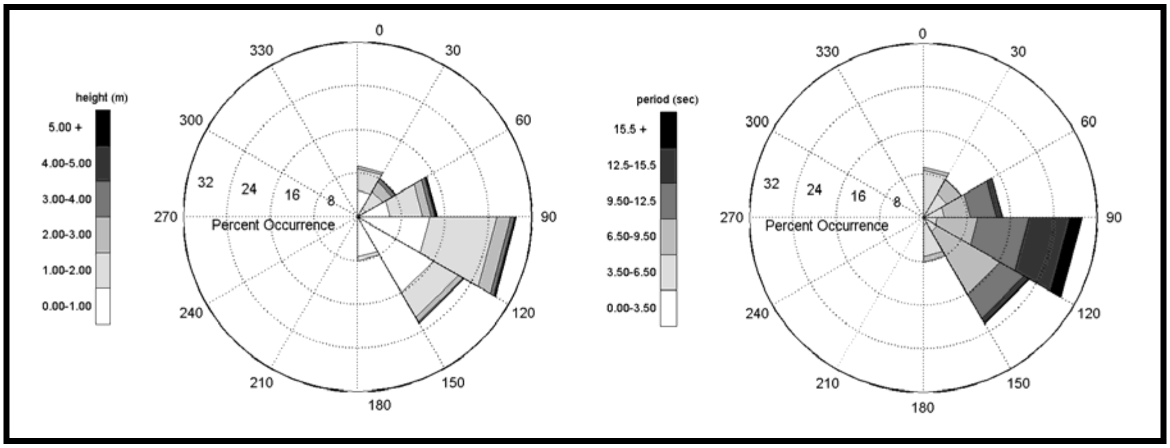

Figure 4-5. WAVETRAN model output for WIS Station AU2056 data transformed to offshore boundary of STWAVE numerical grid. Directions are relative to STWAVE grid orientation, where 90° corresponds to 66° true north, and 0° corresponds to 336° true north.

STWAVE input spectra were developed using a second numerical routine which re-creates a two-dimensional spectrum for each individual wave condition in the transformed WIS record. This 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), as well as wind speed. This method is described by Goda (1985). The frequency spectrum $S(f)$ is computed using the relationship

$$S(f) = 0.257 H_{1/3}^{2} T_{1/3} (T_{1/3} f)^{-5} \exp\left[-1.03 (T_{1/3} f)^{-4}\right] \tag{4.4}$$

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

$$T_{1/3} = 1/(1.05 f_p). \tag{4.5}$$

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

$$S(f,\theta) = S(f)G(f,\theta). \tag{4.6}$$

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

$$G(f,\theta) = G_o \cos^{2s}\left(\frac{\theta}{2}\right) \tag{4.7}$$

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 upon θ and s. The spreading parameter s is evaluated using the expression

$$s = \begin{cases} s_{\max} \cdot (f / f_p)^5 : f \le f_p \\ s_{\max} \cdot (f / f_p)^{-2.5} : f \ge f_p \end{cases} \tag{4.8}$$

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. Finally, the constant G_o is computed by evaluating the integral

$$G_o = \left[\int_{\theta_{\min}}^{\theta_{\max}} \cos^{2s}\left(\frac{\theta}{2}\right) d\theta \right]^{-1}. \tag{4.9}$$

The result is a wave energy spectrum based on parameters from the WIS record, and which distributes spectral energy based on wave peak frequency and wind speed. An example of a two-dimensional spectrum generated by this method is presented in Figure 4-6.

After re-creating a two-dimensional spectrum from the parameters given in the WIS record, each individual spectrum is sorted, or “binned”, by peak direction as well as by peak period. Wave spectra computed from wave parameters that fall within the limits of the individual direction and period bins are added together, and a mean spectrum for all waves in each bin is computed based on the total number of wave events in the bin. In total, seven direction bins and two period bins were used to characterize the wave data. From the 12 total bins, conditions used in the model runs of STWAVE were selected based on the percent occurrence and percent energy for conditions in each bin.

Selected conditions have a percent occurrence greater than one percent, and also contain more than one percent of the energy of the entire wave record. The nine conditions selected for model runs are shown in Table 4-1, with the significant parameters of each input spectrum.

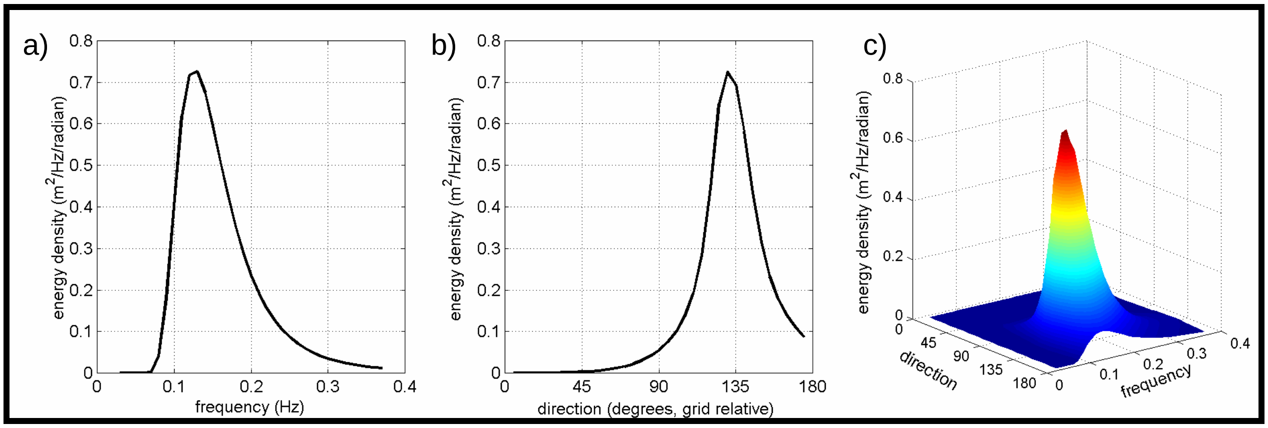

Figure 4-6. Example of STWAVE input spectrum developed using WIS 20-year hindcast data together with the Goda method of computing frequency and direction spectrum. Plots show a) frequency distribution of energy at peak direction, b) directional distribution of energy at peak frequency, and c) surface plot of two-dimensional energy spectrum. Example is model Case 5 (H_{mo} = 0.9 m, θ_{mean} = 130° grid relative).

Table 4-1. Significant parameters of input wave spectra used for existing and post-dredging STWAVE model runs. Storm input conditions are for a simulated 10-year event.

	STWAVE Model Input Condition	Percent Occurrence	H_{mo} Wave Height	Mean Wave Period, T_p	Peak Wave Direction, θ_p	Peak Wave Direction, θ_p	Direction Bin
			(m)	(sec)	(deg. true north)	(grid relative)	(grid relative)
Period Band 1	1	9.4	1.1	5.1	1	25	0-30
	2	8.1	1.9	6.0	21	45	30-60
	3	8.7	1.5	6.7	56	80	60-90
	4	10.1	1.2	7.4	86	110	90-120
	5	16.3	0.9	7.6	106	130	120-150
	6	8.1	0.6	4.6	131	155	150-180
Period Band 2	7	6.0	1.9	11.5	66	90	60-90
	8	19.2	1.5	12.8	71	95	90-120
	9	6.3	1.3	11.3	101	125	120-150

4.1.1.2 Grid Development

Together with the input spectra, three bathymetry grids were developed for the existing and post-dredging scenarios. Three coarse grids were developed to have the same geographical coverage, and differ by only modifications to bathymetry in the borrow area. One grid serves to provide existing wave conditions. The other two grids included dredged depths at Sites 1, 2, and 4, and alternately, Site 3 east or 3 west. The NOS was the primary source of bathymetric data used to create the grids (NOS, 1998). However, these data were supplemented by more recent bathymetric data. A contour plot of the post-dredging grid is shown in Figure 4-7. Depths at the offshore open boundary vary between 31 and 19 m, with a mean depth of approximately 25 m.

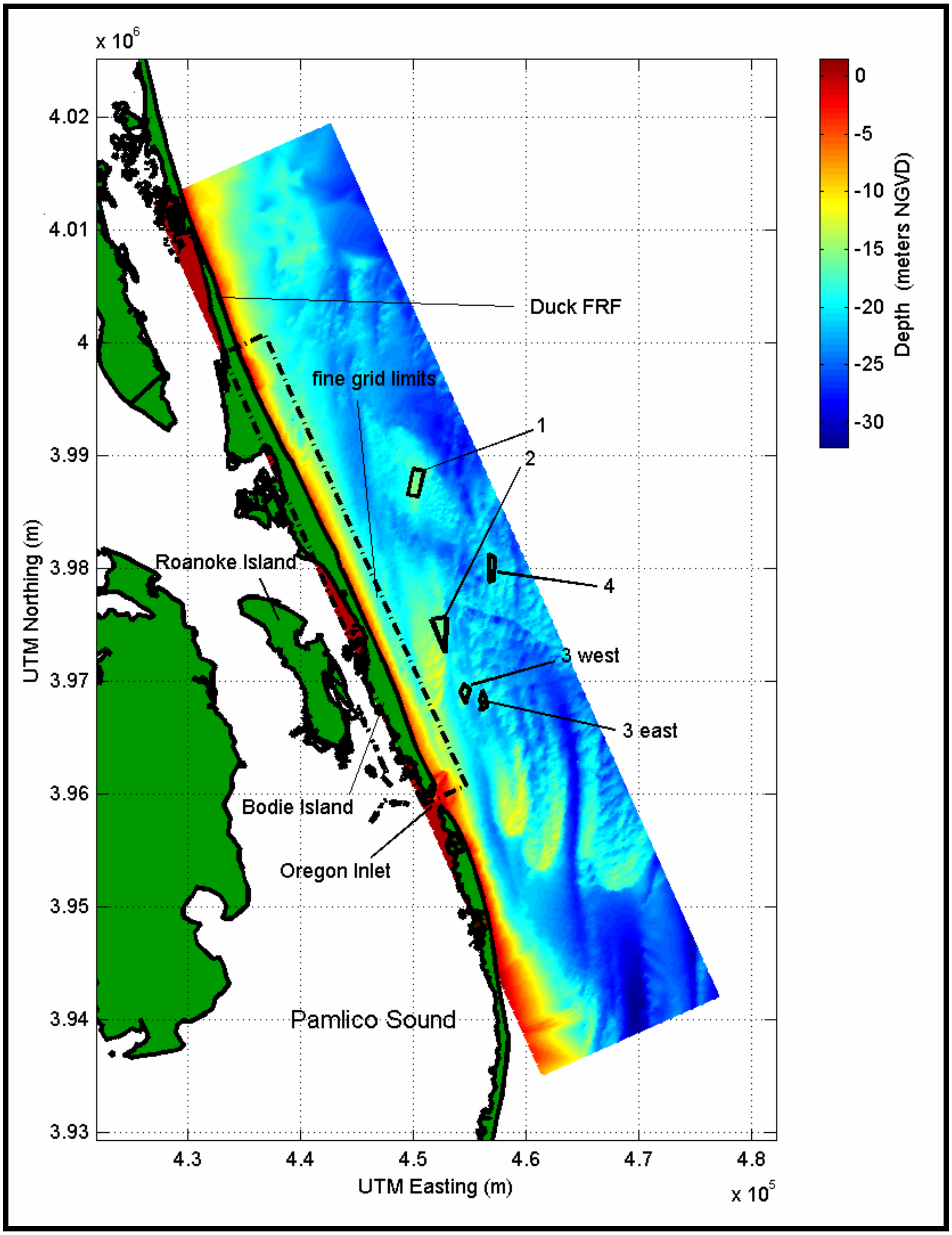

Figure 4-7. Color contour plot of coarse model grid (200 m x 200 m grid spacing) used with STWAVE. Depths are relative to NVGD 29. Borrow site locations are indicated by solid black lines, and fine grid limits are indicated by a dashed line.

Each coarse grid covers an area that extends approximately 17 km offshore and 85 km alongshore. The geographical limits of the grids were chosen based on the wave conditions selected for model runs. Wave conditions with relatively small angles to the shoreline require a wide grid so that the site of interest (i.e., the borrow site and affected shoreline) does not fall within the "shadow" of the lateral grid boundaries. The grids are made up of 87 cells in the offshore direction by 425 cells in the alongshore direction, for a total of 36,975 grid cells, each with a spacing of 200 m. The grid axes are rotated counterclockwise by 24° to match the orientation of the shoreline in this area.

In addition to the four coarse grids, a single fine grid was developed to obtain greater resolution of waves in the nearshore area behind the borrow site (Figure 4-8). The same fine grid was used for both existing and post-dredging conditions. This fine grid extends approximately 3 km offshore and 18 km alongshore. This grid is made up of 300 cells in the offshore direction and 1,250 cells in the alongshore direction, for a total of 375,000 grid cells. The alongshore and cross-shore dimension of each cell is 20 m. Boundary conditions (wave spectra) for the fine grid were extracted from runs of the coarse grids.

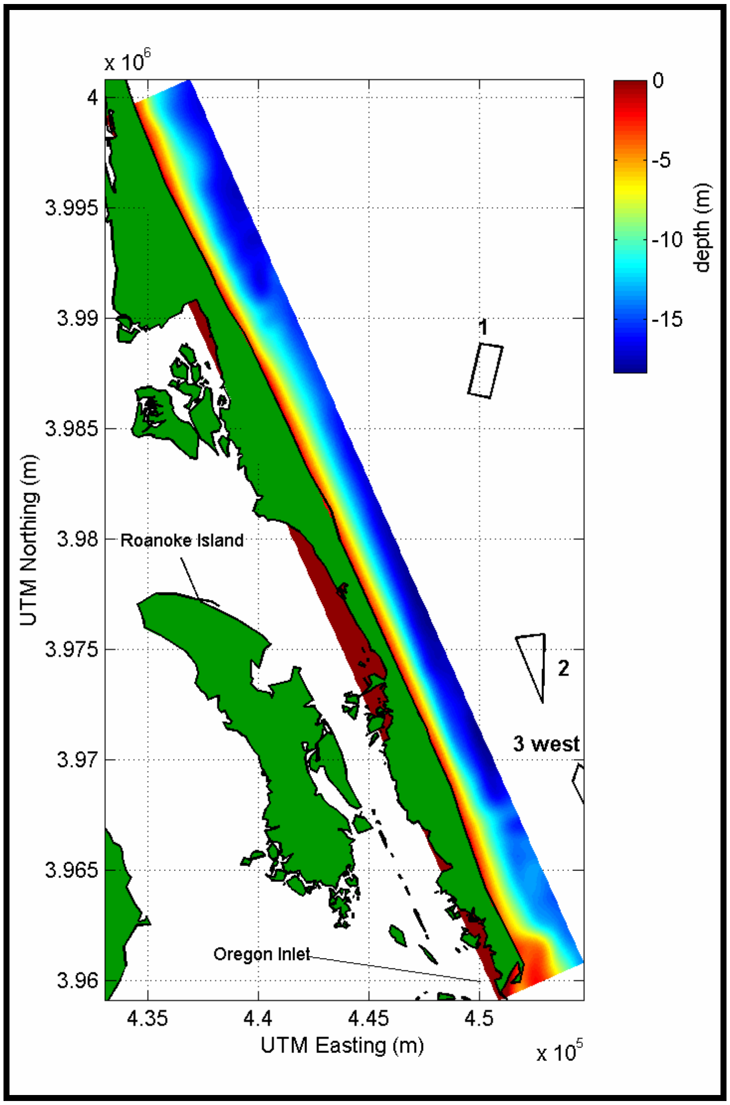

Figure 4-8. Color contour plot of fine model grid (20 m x 20 m grid spacing) used with STWAVE. Depths are relative to NGVD 29. Borrow site location is indicated by solid black line, and fine grid limits are indicated by dashed line.

4.1.2 Sediment Transport Potential

As a first step in evaluating sediment transport along the coastline of the North Carolina Outer Banks, calculations of sediment transport potential were performed to indicate the maximum quantity of transport possible based on a sediment-rich environment. Results from the spectral wave modeling formed the basis for changes in sediment transport rates along the beach because wave-induced transport is a function of various parameters (wave breaking height, wave period, and wave direction). Longshore transport depends on long-term fluctuations in incident wave energy and the resulting longshore current; therefore, annual transport rates were calculated from long-term wave statistics.

The sediment transport equation used for the longshore analyses is based on the work of the USACE (1984). In general, the longshore sediment transport rate is assumed to be proportional to the longshore wave energy flux at the breaker line, which is dependent on wave height and direction. Because the transport equation was calibrated in sediment-rich environments, it typically over-predicts sediment transport rates. However, it provides a useful technique for comparing erosion/accretion trends along the shoreline of interest.

Sediment transport computations were based on wave information at breaking for each grid cell along the modeled coastline. This shoreline segment incorporates the influence of all changes to the nearshore wave climate associated with proposed dredging activity. Computations of sediment transport rates for each of the nine wave conditions were performed and then weighted by the annual percentage occurrence. Sediment transport potential was computed for existing and post-dredging conditions.

The volumetric longshore sand-transport rate, Q_ℓ, past a point on a shoreline is computed using the relationship:

$$Q_\ell = \frac{I_\ell}{(s-1)\rho g a'} \tag{4.10}$$

where I_ℓ is the immersed-weight longshore sand-transport rate, s is the specific gravity of the sediment, a' is the void ratio of the sediment, g is the acceleration of gravity, and ρ is the density of seawater.

For this study, I_ℓ was computed using two methods. The first method is commonly referred to as the CERC formula,

$$I_\ell = KP_{\ell s} \tag{4.11}$$

where K is a dimensionless coefficient and $P_{\ell s}$ is the longshore-directed wave energy flux computed using the following relationship:

$$P_{\ell s} = \frac{\rho g^{3/2}}{16\sqrt{\gamma}} H_{sb}^{5/2} \sin 2\alpha_b \tag{4.12}$$

where H_{sb} is the significant wave height at breaking, γ is the coefficient for the inception of wave breaking ($\gamma = H_b/h_b$), and α_b is the breaking wave angle. A value of K=0.4 was used for this study, appropriate for significant wave heights (computed by STWAVE), rather than the more familiar value K=0.77, which is used with RMS wave height.

The second method used to compute the immersed-weight longshore sand-transport rate was described by Kamphuis (1990). This method is a modification to the original CERC formula that adds a dependency on median grain diameter of beach sand and the surf similarity parameter (Irabarren number), ξ_b, which is expressed as

$$\xi_b = \frac{m}{\left(H_b / L_0\right)^{0.5}} \tag{4.13}$$

where m is the bottom slope, H_b is the wave-breaker height, and L_o is the incident deep-water wave length. The complete expression of Kamphuis is given by

$$I_\ell = K^* \rho g \left(\frac{g}{2\pi} \right)^{0.75} \xi_b T^{0.5} \left(m d_{50} \right)^{-0.25} H_s^{2.5} \sin^{0.6}\left(2\theta_b \right) \tag{4.14}$$

where the coefficient K^* = 0.0013.

4.2 MODEL RESULTS

Due to the redistribution in wave energy and alteration of wave directions resulting from offshore sand excavation, changes to the longshore sediment transport patterns will occur. Depending on the net direction of local sediment transport, the influence of borrow site conditions can either increase or decrease net littoral drift.

4.2.1 Wave Modeling

From existing conditions model results, it can be seen that bottom features offshore the Outer Banks modify the wave field as it propagates shoreward. Model output presented in Figure 4-9 shows how waves respond to offshore shoals, even in relatively deep water (>15 m). For example, for the shoal feature in the vicinity of Resource Area 1, wave heights behind the shoal are about 0.4 m greater than wave heights at the northern and southern limits of the shoal. The shoal refracts the wave field, causing a slight focusing of wave energy behind the feature. Because energy is conserved, the focusing of wave energy behind the shoal causes a reduction of energy at the northern and southern edges of the shoal, which is apparent by the reduced wave heights in these areas.

In addition to the effects of bottom features far offshore, waves are refracted by the straight and parallel bottom contours in the nearshore. In Figure 4-9, fine grid model results show how wave directions change as the wave field propagates shoreward. For this southeast wave condition (as in Figure 4-10), waves refract and the mean direction of wave propagation becomes more shore-normal (perpendicular to the shoreline). In addition to the change in wave direction, wave heights also are modified by nearshore bathymetry. Waves begin to shoal (increase in height) about 500 m offshore, and increase in height by 0.2 m before breaking begins. Wave heights are reduced as energy dissipates in the surf zone, which is about 60 m wide in this example.

Output from post-dredging model runs indicate that wave heights within the borrow site are reduced relative to existing conditions, and this effect is more pronounced in cases that have greater wave heights. Wave fields landward of proposed borrow sites are modified by refraction. As waves propagate across a borrow site (deeper water than the surrounding area),

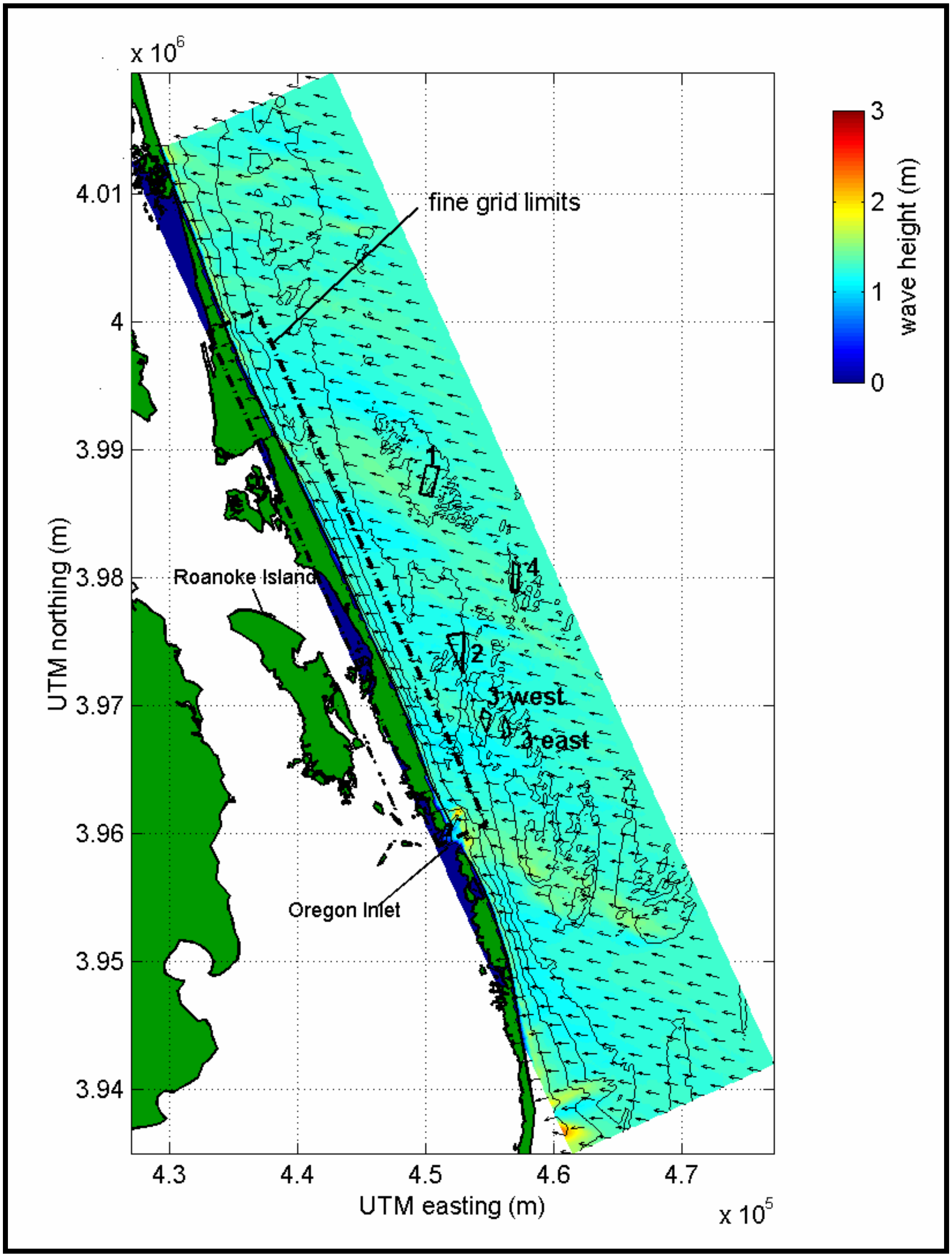

Figure 4-9. Example STWAVE output for coarse grid (200 m x 200 m cell) model of offshore North Carolina, model case 9 (H_{mo} = 1.3 m, T_p = 11.3 sec). Color contours show H_{mo} wave height. Vectors indicate wave *mean* direction. Bottom bathymetry contours are shown as light black lines. Fine grid limits are indicated by dashed line.

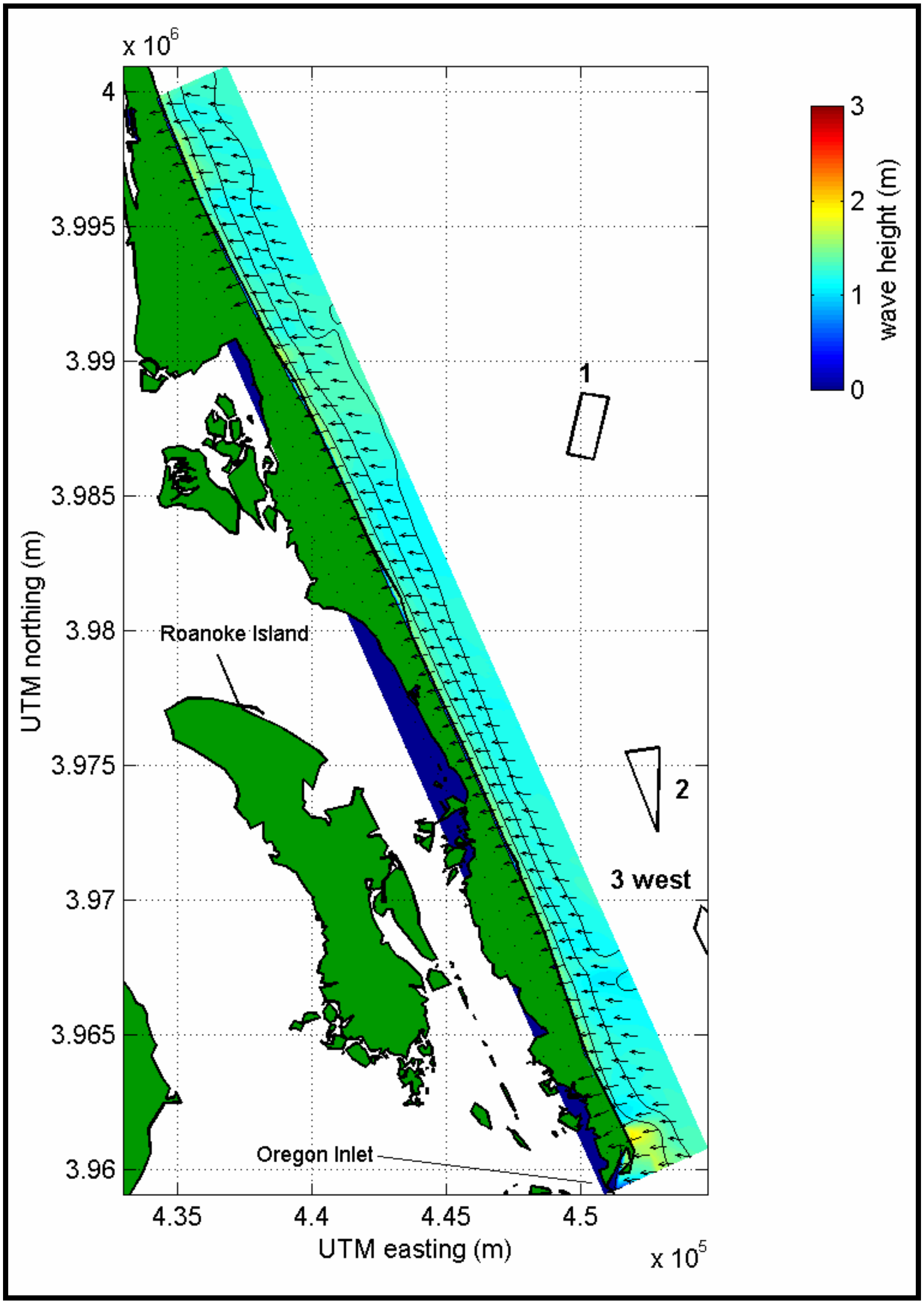

Figure 4-10. Example STWAVE output for fine grid (20 m x 20 m cell) model of offshore North Carolina, model case 9 (H_{mo} = 1.3 m, T_p = 11.3 sec). Color contours show H_{mo} wave height. Vectors indicate wave mean direction. Bottom bathymetry contours are shown as light black lines. Fine grid limits are indicated by dashed line.

wave refraction tends to bend waves away from the center of the excavation area and toward the shallower edges. The net effect is to create a "shadow" zone of reduced wave energy immediately landward of the borrow site and a zone of increased wave energy updrift and downdrift of the borrow site.

This shadowing effect is apparent in model results presented in Figure 4-11. In this figure, color contours represent wave height difference between model results computed for existing and post-dredging conditions. In the immediate vicinity of Site 2, for example, wave heights increased by a maximum of 0.05 m at the northern and southern edges of the borrow site and decreased by a maximum of 0.06 m behind the borrow site. In Figure 4-12, fine grid model results for the same wave condition illustrate that the magnitude of change in wave height has decreased closer to shore, as the color contours indicate a 0.01 m increase and 0.03 m decrease from existing conditions.

Because spectral wave model results are being used, and because different frequencies in the spectrum are refracted by varying degrees at the borrow site, the areas of increased and reduced wave height gradually diffuse as the wave field approaches the shore. A result of this energy diffusion is that the length of shoreline affected by a borrow site can be considerably longer than the borrow area. For this particular example, the length of affected shoreline is approximately three times longer than the alongshore dimension of the borrow site.

Another result of the gradual diffusion of wave energy caused by refraction of the wave spectrum is shown in Figure 4-11. In this figure, borrow sites farther offshore affect a longer length of shoreline, however, the actual magnitude of impact is reduced because the affected wave field has a greater distance over which to dissipate energy. This is evident in a comparison of the effect of Sites 1 and 2. Site 1 is larger than Site 2, but it is located farther offshore. Therefore, wave height change between existing to post-dredging conditions at the shoreline is smaller for Site 1 than changes resulting from the same waves propagating over Site 2.

Figure 4-11 demonstrates how borrow site geometry influences potential shoreline impacts. In this example, wave field modifications from Sites 2 and 3 west illustrate that Site 2 has a greater impact on nearshore wave heights. Though both sites are excavated to the same depth (3 m), Site 3 west has a smaller surface area than Site 2. Site 3 west also is located in deeper water, as the mean depth at the site is approximately 2 m deeper than Site 2. The increased impact resulting from sand excavation at Site 2 occurs due to the combination of these two characteristics (size and depth).

Additional examples of wave model output for offshore North Carolina are illustrated in Figures 4-13 (Case 2) and 4-14 (Case 8). For Case 2, shoals offshore Oregon Inlet produce a small increase in wave height landward of the shoals, with a corresponding small decrease in wave height seaward of the shoals. Otherwise, no significant shoaling or refraction is observed in this relatively short period wave case.

Model output for wave Case 8 (see Table 4-1) is shown in Figure 4-14. This wave condition has a significantly longer period than Case 2, and as a result, waves are more affected by offshore bathymetry gradients. Although the direction of wave propagation is not modified as much as was indicated in previous examples, wave heights have changed significantly (e.g., a maximum height of 2.4 m at the southern side of Oregon Inlet) relative to offshore conditions. At the offshore shoals directly east of the inlet, wave heights increase approximately 0.7 m over the offshore boundary condition. Several shoal areas along the modeled coastline show similar impacts on wave heights, including the area encompassing the two modeled borrow sites.

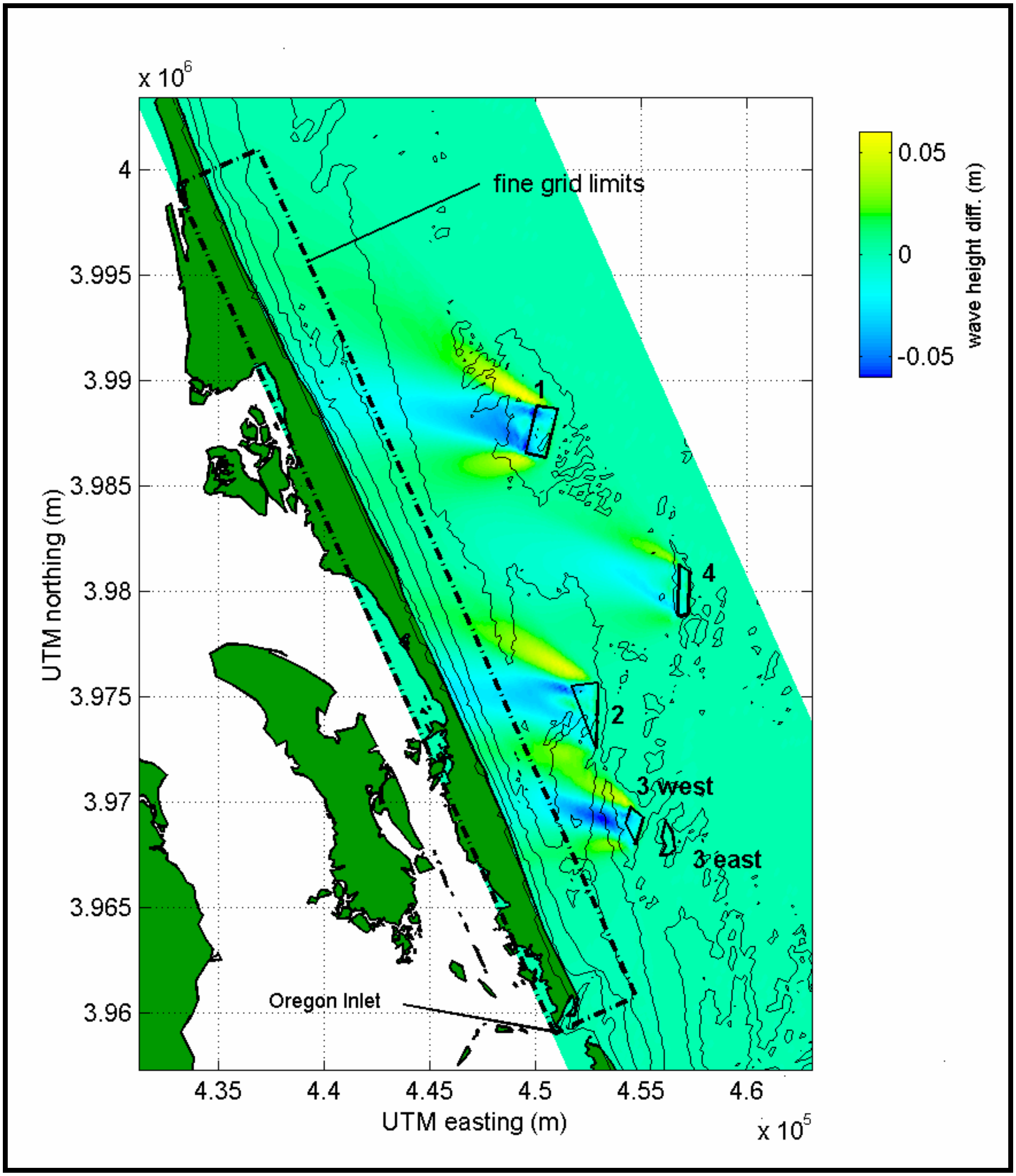

Figure 4-11. Wave height difference plot between existing and post-dredging conditions ($H_{difference} = H_{post} - H_{pre}$) for coarse grid (200 m x 200 m cell) model of offshore North Carolina, model case 9 (Hmo = 1.3 m, Tp = 11.3 sec) , for run which included excavation at Sites 1, 2, 3 west, and 4. Bottom bathymetry contours are shown as light black lines.

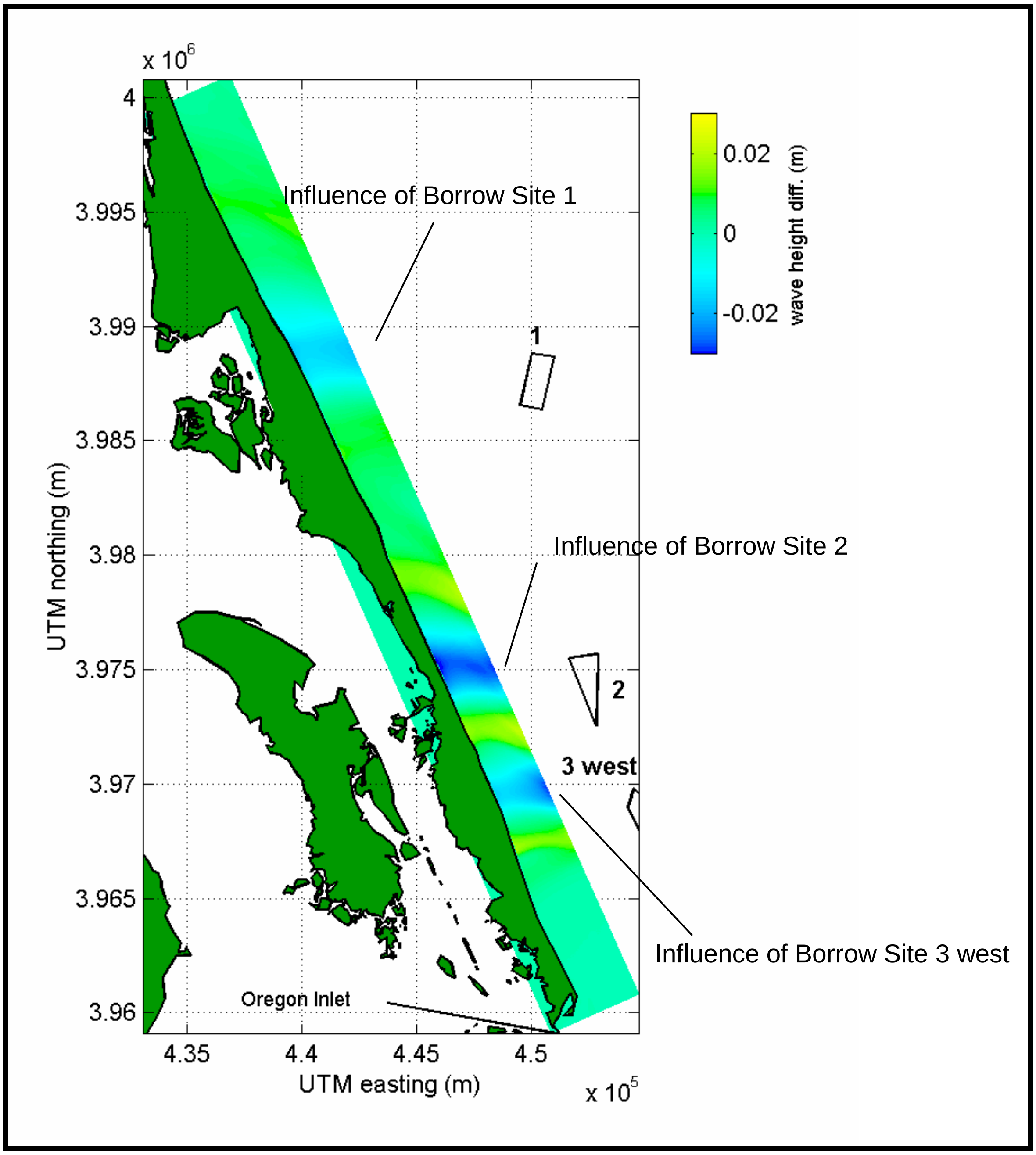

Figure 4-12. Wave height difference plot between existing and post-dredging conditions ($H_{difference} = H_{post} - H_{pre}$) for fine grid (20 m x 20 m cell) model of offshore North Carolina, model case 9 (H_{mo} = 1.3 m, T_p = 11.3 sec), for run which included excavation at Sites 1, 2, 3 west, and 4. Bottom bathymetry contours are shown as light black lines. Fine grid limits are indicated by dashed line.

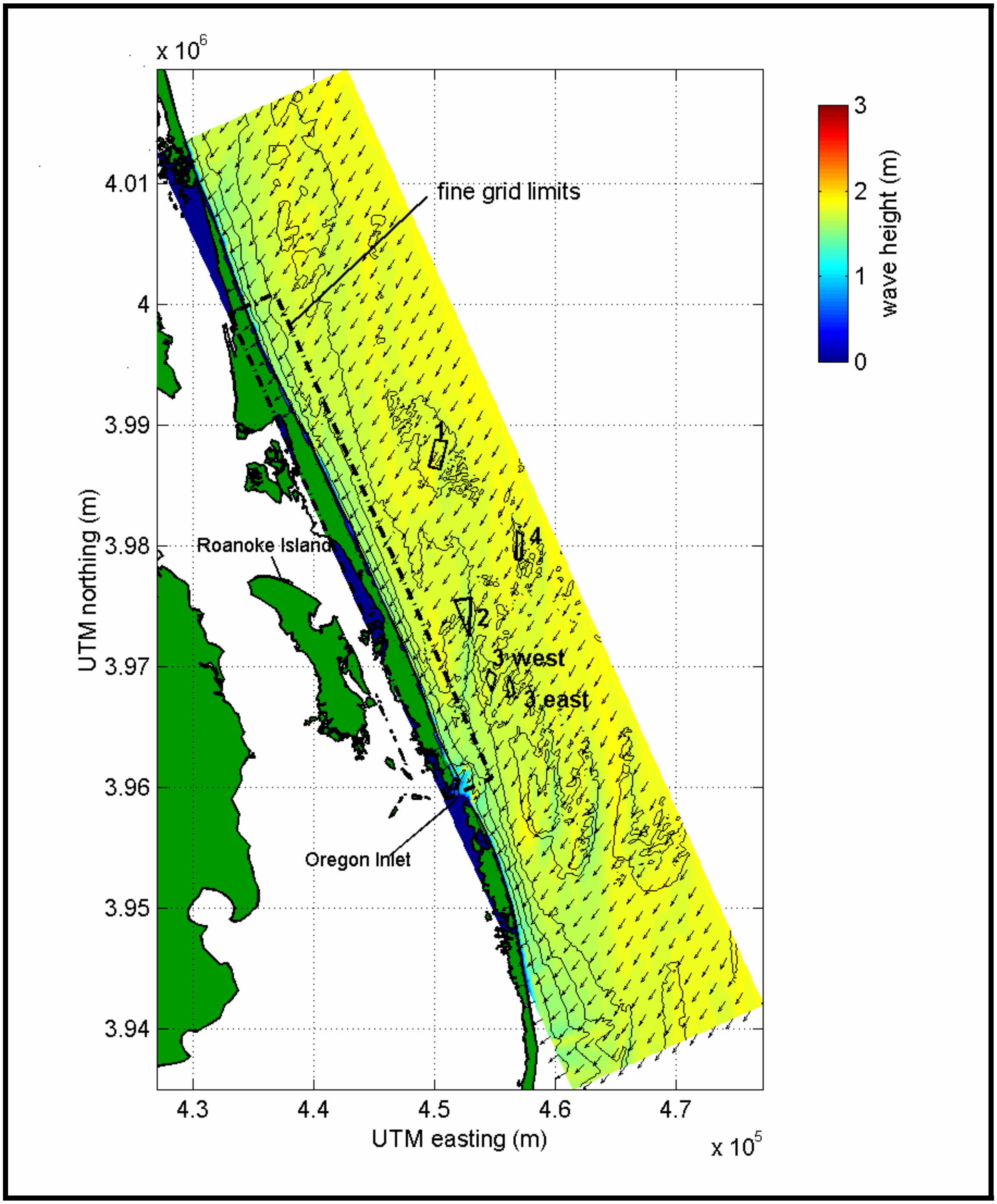

Figure 4-13. Plot of STWAVE model output for offshore North Carolina wave Case 2 ($H_s = 1.9$ m, $T_{peak} = 6.0$ sec, $\theta_{peak} = 21$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.

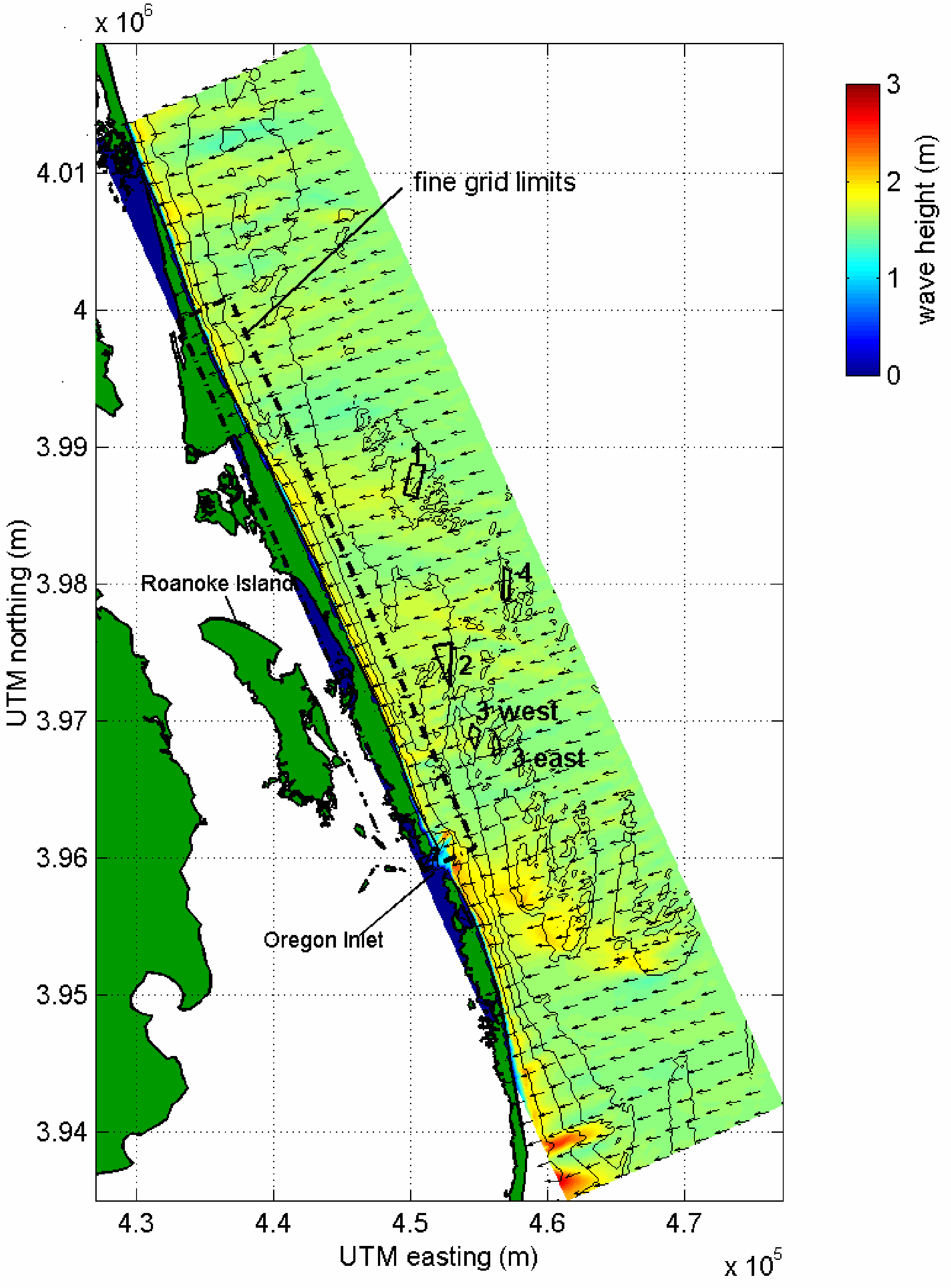

Figure 4-14. Plot of STWAVE model output for offshore North Carolina wave Case 8 ($H_S = 1.5$ m, $T_{peak} = 12.8$ sec, $\theta_{peak} = 71$ deg). Color contours indicate wave height, and vectors show mean direction of wave propagation.

Plots of wave height change from existing and post-dredging conditions at Sites 1, 2, 3 west, and 4 are shown in Figures 4-15 and 4-16 for wave Cases 2 and 8. For Case 2 results (Figure 4-15), the area of influence for the combination of the four modeled sites extends approximately 40 km along the coastline. The long extent of influence is the result of the approach angle for offshore waves. The greatest increase in wave heights resulting from potential dredging was south of Site 2, where wave heights increased 0.09 m over existing conditions. The area of greatest wave height reduction is located near Site 1, where wave heights decreased 0.09 m from existing conditions.

Figure 4-16 presents the wave height difference plot for Case 8 (see Table 4-1). Sites 2 and 4 have an observable overlapping region of influence, as Site 4 is located offshore Site 2, along the direction of wave propagation. The area of maximum increased wave heights for post-dredging conditions is located at the northern-most corner of Site 1, where wave heights increase 0.09 m over existing conditions. The area of maximum wave height decrease is located near Site 1, where wave heights are reduced by 0.12 m from existing conditions. This area of maximum reduced wave heights occurs at the landward corner of Site 1. For Case 8, the length of affected shoreline, to where borrow site “shadows” propagate, extends approximately 40 km, starting from about 3 km north of Oregon Inlet.

4.2.2 Sediment Transport Potential

Comparisons of average annual sediment transport potential were performed for existing and post-dredging conditions to indicate the relative impact of dredging to longshore sediment transport processes. Sediment transport potential is a useful indicator of shoreline impacts caused by offshore borrow sites because the computations include the borrow site influence on wave height and direction. For the study area, the net sediment transport potential associated with average annual conditions was computed. For comparison, transport potential was computed using both the coarse grid and fine grid model results.

Both net and gross sediment transport potential results are shown in Figure 4-17, for a 35-km stretch of coastline from Oregon Inlet to approximately 9 km south of the USACE Duck FRF. Results were computed using existing wave conditions and post-dredging conditions for two alternate borrow site configurations, 1) Sites 1, 2, 3 east, and 4 modeled together, and 2) Sites 1, 2, 3 west, and 4 modeled together. The plot of gross and net transport potential indicates that there is a reversal of the direction of transport south of 3,970,000 m UTM northing, at Bodie Island. North of this spot, net transport is to the north, while south of this point to Oregon Inlet, the net transport is strongly to the south. The computed north- and south-directed transport potential shows that transport is strongly bi-directional, with a gross transport magnitude of approximately 600,000 m^3/yr far north of Oregon Inlet, but with a net transport magnitude of only 250,000 m^3/yr. Closer to the inlet, the littoral drift becomes more uni-directional and to the south, with gross and net transport potential magnitudes peaking at over 600,000 m^3/yr.

A plot of transport potential change for the two borrow site configurations also is presented in Figure 4-17. The maximum negative change (post-dredging minus existing condition) in computed net sediment transport potential occurs with the second configuration (Sites 1, 2, 3 west, and 4), where the peak change is -34,000 m^3/yr, or 45% of the net transport potential at this point. The maximum positive change is approximately 14,000 m^3/yr or only 8% of the net transport potential computed at this point.

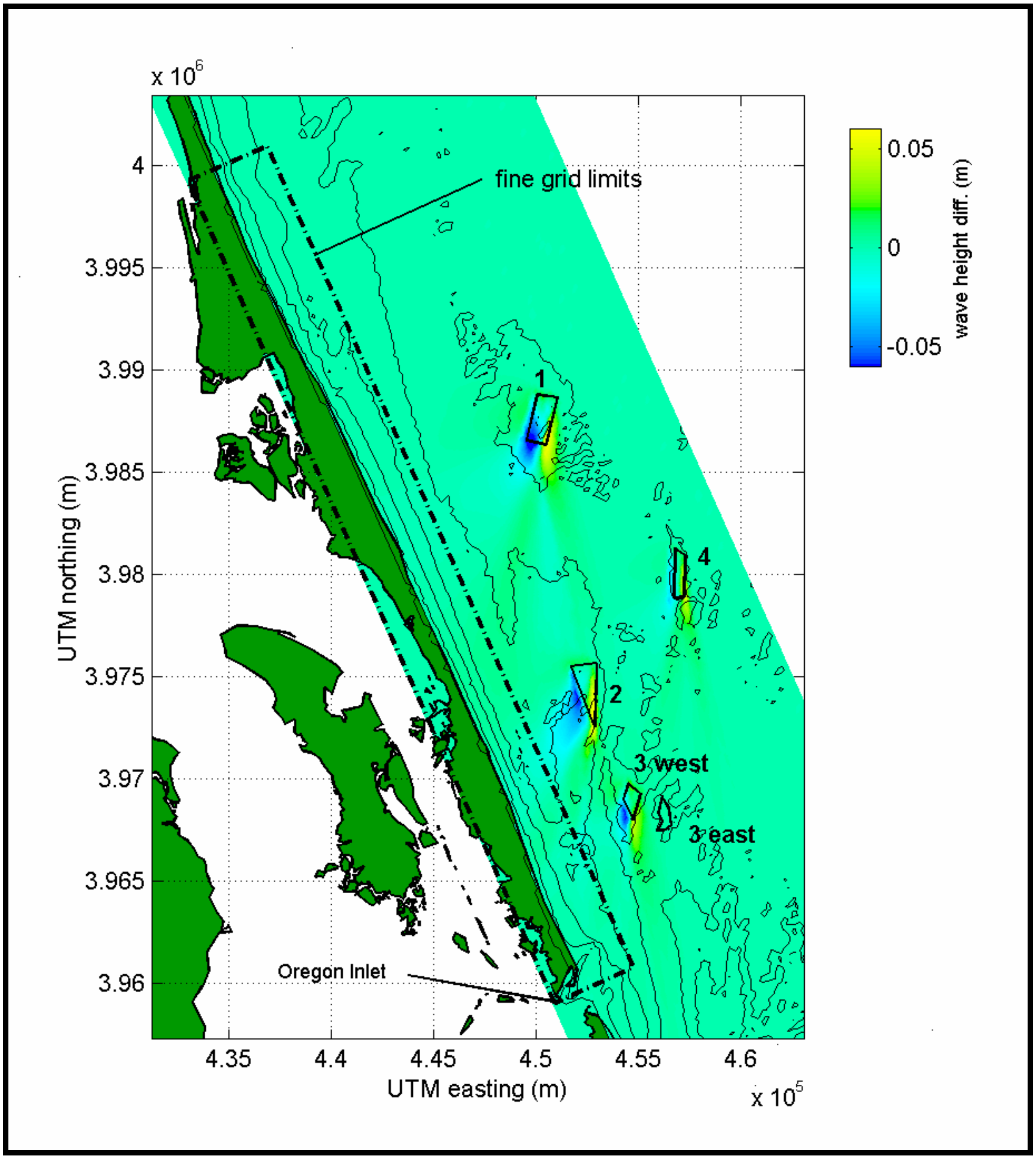

Figure 4-15. Plot of wave height change between existing and post-dredging ($\Delta = H_{post}-H_{pre}$) conditions at Borrow Sites 3 east and 3 west for STWAVE model output for offshore North Carolina wave Case 2 ($H_s = 1.9$ m, $T_{peak} = 6.0$ sec, $\theta_{peak} = 21$ deg).

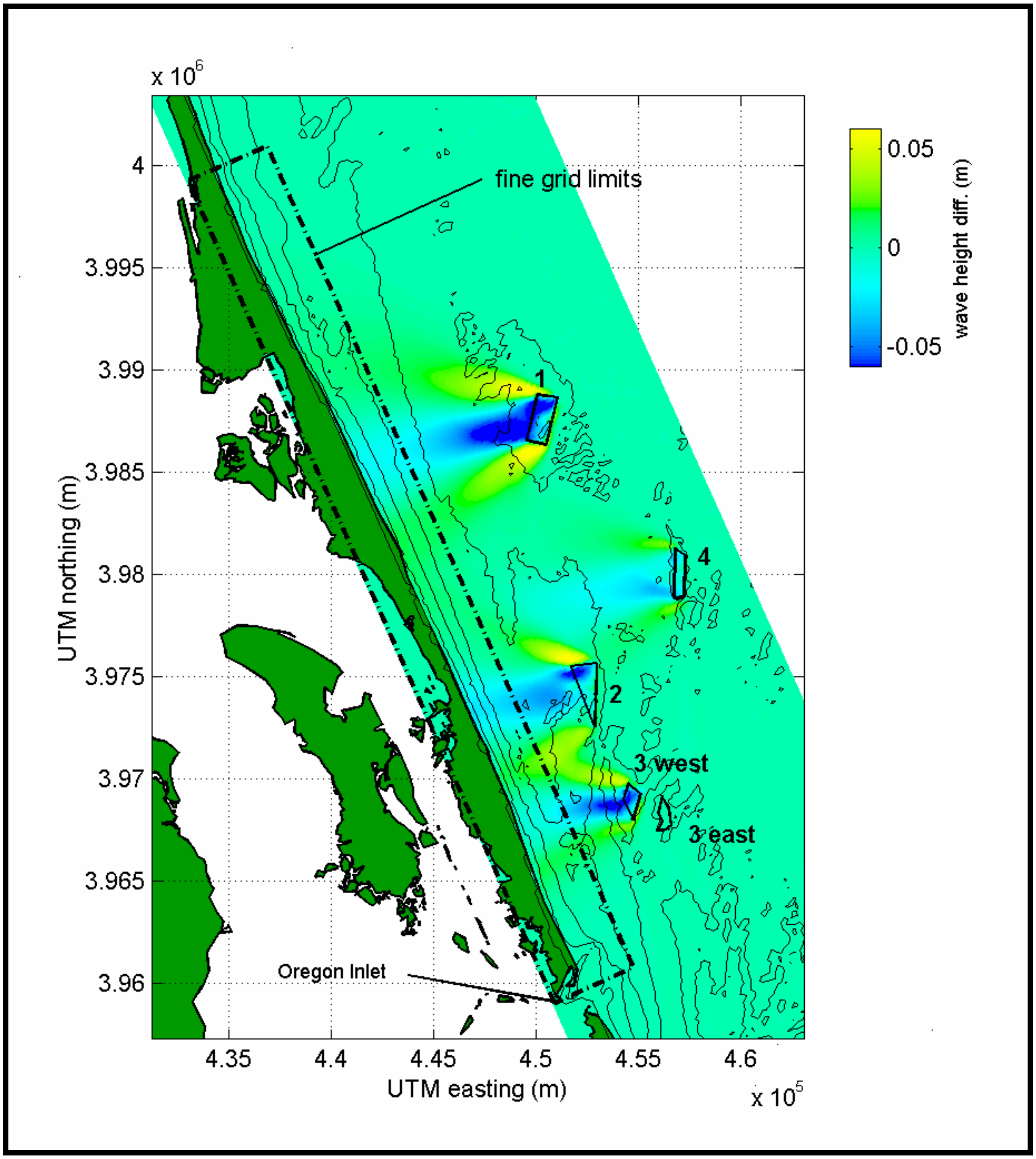

Figure 4-16. Plot of wave height change between existing and post-dredging ($\Delta = H_{post}-H_{pre}$) conditions at Borrow Sites 3 east and 3 west for STWAVE model output for offshore North Carolina wave Case 8 ($H_s = 1.5$ m, $T_{peak} = 12.8$ sec, $\theta_{peak} = 71$ deg).

4.2.2.1 Littoral Drift Comparison with Existing Studies

Longshore transport potential computations are contrary to the classical assumption that net transport along the entire Outer Banks is southerly. A summary of past efforts to quantify transport volumes at the Outer Banks was given by Inman and Dolan (1989). Results for this study indicate that a nodal point (where net transport direction changes) exists far north of the present study area, at False Cape, VA, and that south of this point net transport is southerly with a magnitude of 660,000 m^3/yr (Figure 4-18). Other studies cited by Inman and Dolan (1989) agree with this result. Net transport rates at Nags Head, NC (approximately 3,980,000 UTM northing) were estimated at 686,000 m^3/yr to the south by the USACE, Wilmington District (1980), and 817,000 m^3/yr to the south by Birkemeier et al. (1981).

Of these three historical estimates of the net magnitude and direction of littoral drift in this region, results of Inman and Dolan (1989) are based on the most rigorous method. For that study, the original WIS Phase III data (Jensen, 1983) was refracted to breaking depth for stations along the North Carolina and Virginia coastlines (Stations 77 to 87). Estimates determined for the two other studies (USACE, Wilmington District, 1980; Birkemeier et al., 1981) depended on long-term wave height data collected at the Nags Head pier, and a record of visually observed wave directions.

This present study has benefited from updated WIS offshore wave records, and a long-term directional wave time series available from the USACE FRF. A comparison between the most recent WIS hindcast record (refracted to a depth of 10 m), the original WIS Phase III hindcast, and the long-term data record collected at the USACE FRF at Duck, NC is presented in Figures 4-19, 4-20, and 4-21. In Figure 4-19, a rose plot of the original WIS Phase III data (Station 83) at Duck, NC shows how wave heights are distributed by direction, oriented to the shoreline. Waves are widely spread in this hindcast, but there is an apparent bias to larger waves (more energy) propagating from the north, which would support the net southerly drift determined by Inman and Dolan (1989). In contrast, the recent (1990 to 1999) directional wave data collected at the Duck FRF and the updated WIS hindcast data show a different trend. Recent data sets illustrate that wave occurrences are focused more from directly offshore (compared with WIS Phase III data). In addition, more energy propagates from the south, which indicates greater northerly-directed transport potential (consistent with the results of this study).

An additional comparison between the three data sets is presented in Table 4-2 and Figure 4-22. Table 4-2 shows the distribution of wave energy (proportional to height squared) separated into six bins oriented to the shoreline azimuth. There is good correlation between the wave energy distribution of the recent WIS hindcast data and the Duck FRF directional wave data. The energy distribution of the old WIS Phase III data is significantly different from the other two sets in this comparison. This difference is also observed in the histogram plot in Figure 4-22. This plot shows that the old WIS Phase III data has more energy in bins that would tend to cause net southerly littoral drift, in contrast to the updated WIS and the Duck data, which show more energy in bins that would tend to cause net northerly littoral drift. All three of these data sets show a similar tendency for a strongly bi-directional gross transport, where the magnitude of gross transport (the sum of northerly and southerly drift) is significantly greater than the observed net transport.

Good agreement between recent WIS hindcast data and directional wave gage data from the FRF provides confidence in the computed net transport potential along the shoreline between Oregon Inlet and the FRF.

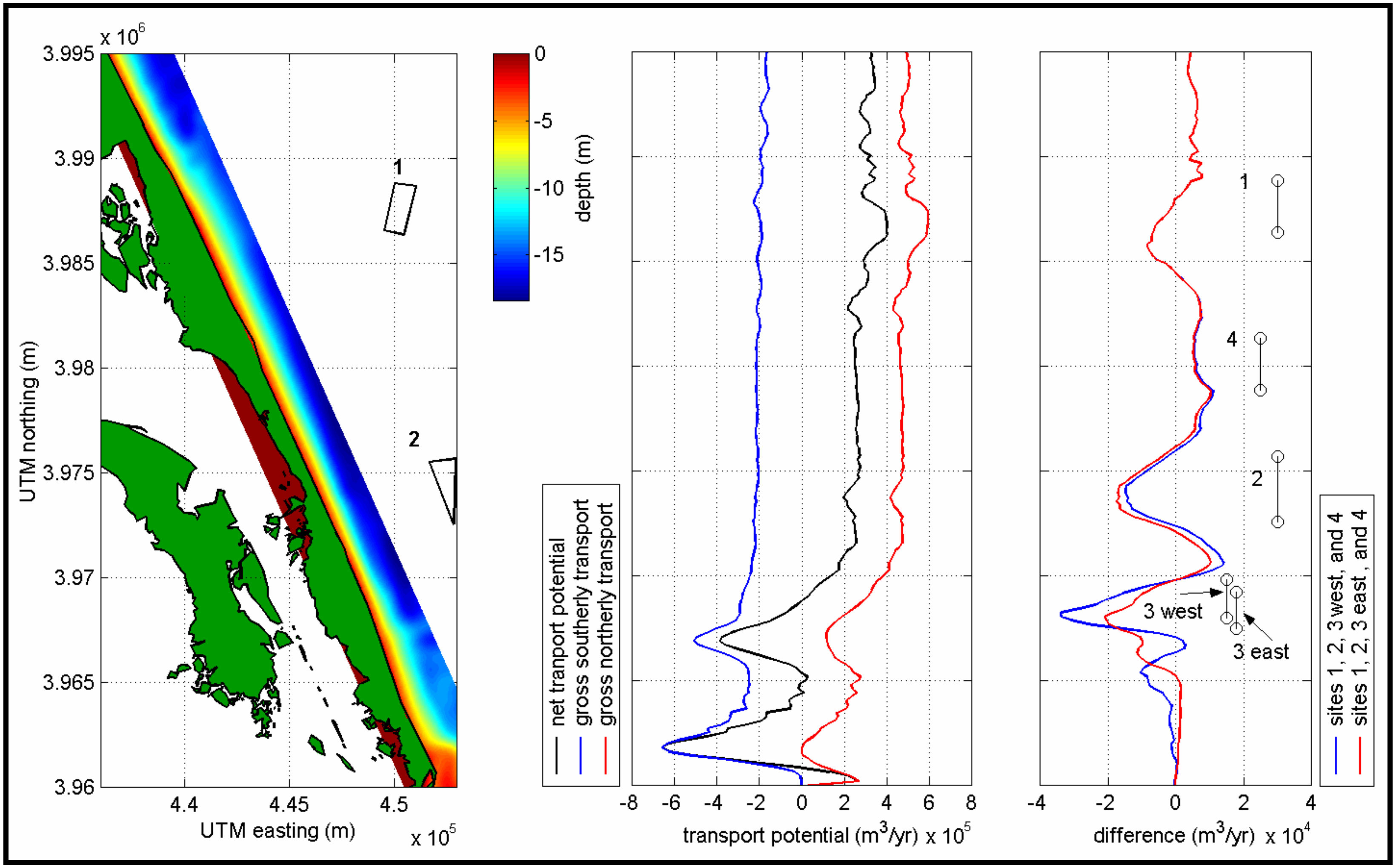

Figure 4-17. Plot of computed transport potential for existing conditions, and transport potential difference between existing and post-dredging conditions for modeled cases where Sites 3 east and 3 west are included alternately. The middle plot shows computed net and gross south and north directed transport for wave conditions derived from 20-year WIS hindcast. The right-hand plot shows change in transport from existing to post-dredging conditions, for Sites 1, 2, and 4, modeled with 3 east and 3 west separately.

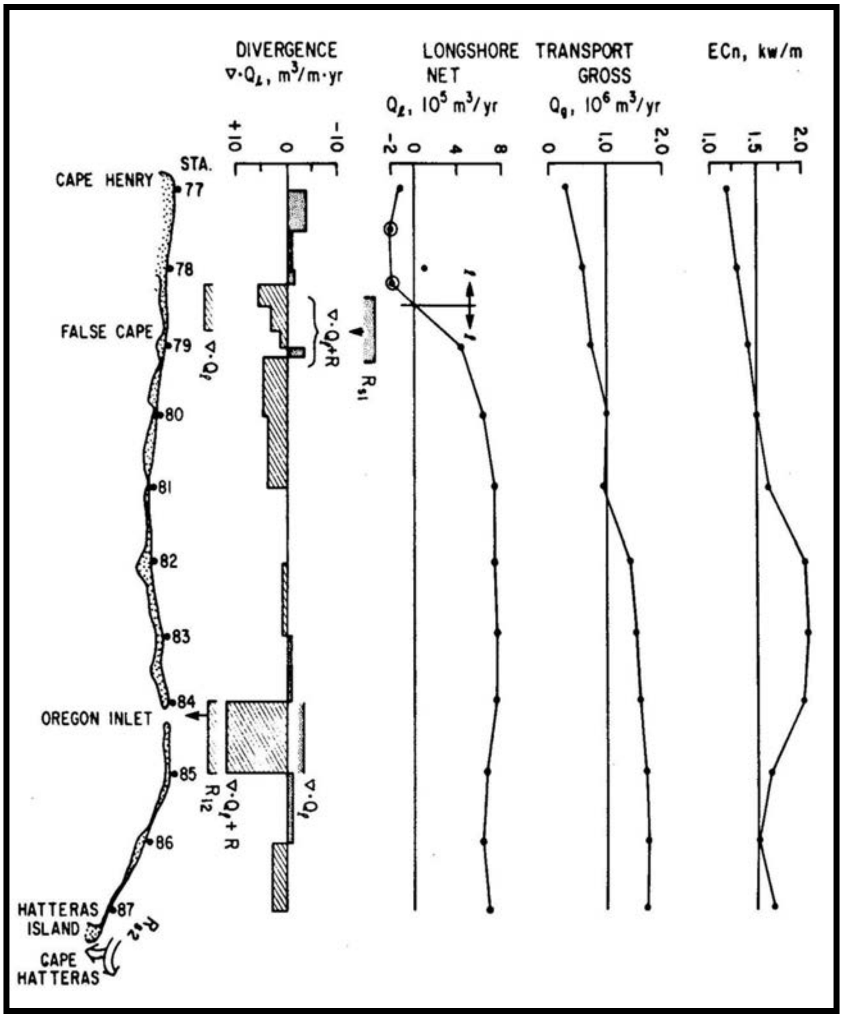

Figure 4-18. Wave energy flux (ECn) and sand transport potential along the Hatteras littoral cell, using wave climate data from the original WIS Phase III simulations (from Inman and Dolan, 1989).

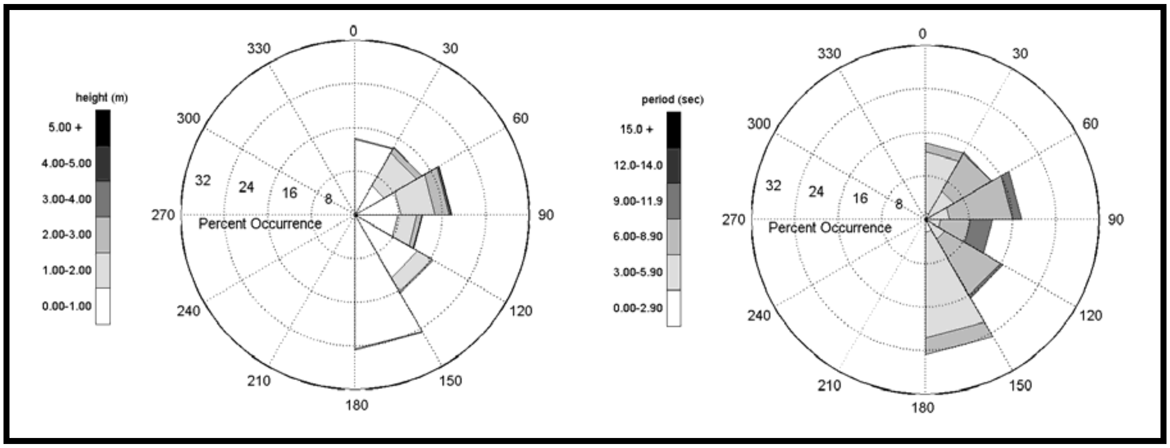

Figure 4-19. WIS Phase III hindcast data for Station 83, for the simulation period from January 1956 through December 1975. Directions are relative to approximate shoreline orientation (340°) at Duck, NC (20° on these plots corresponds to 0° true north).

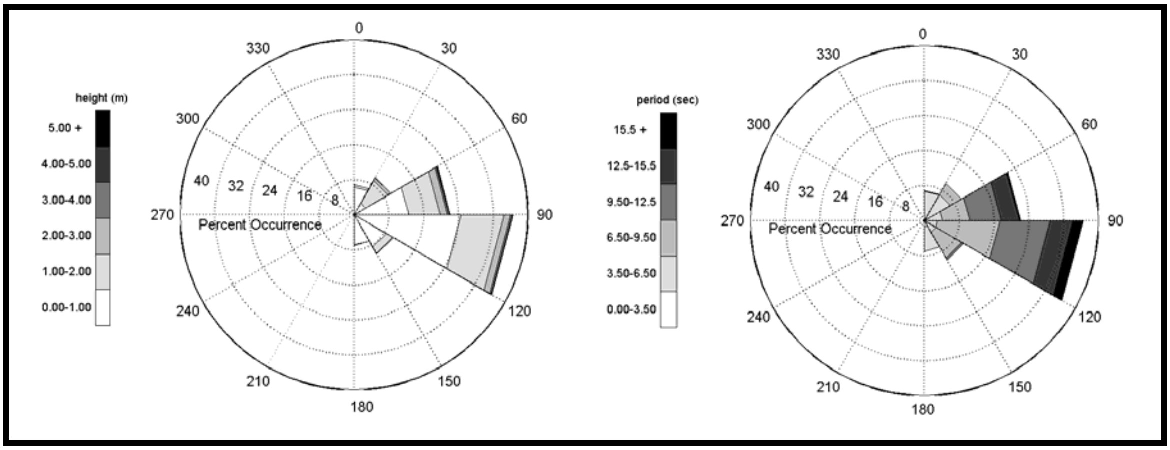

Figure 4-20. WAVETRAN output using WIS Station AU2056. Wave record is refracted into 10 m water depth corresponding to WIS Phase III depth. Directions are relative to approximate shoreline orientation (340°) at Duck, NC (20° on these plots corresponds to 0° true north).

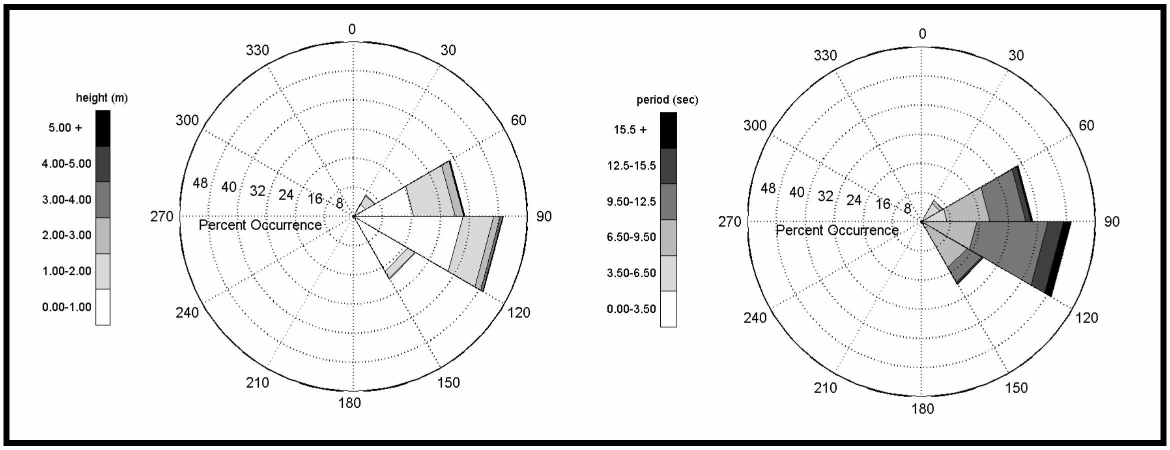

Figure 4-21. Duck FRF data for 8 m directional wave array (January 1990 to December 1999). Directions are relative to approximate shoreline orientation (340°) at Duck, NC (20° on these plots corresponds to 0° true north).

Table 4-2. Comparison of wave energy distribution between updated WIS record (transformed into 10 m water depth), FRF 8 m array record, and original WIS Phase III record. Absolute difference values show percentage difference of FRF 8 m array and original WIS Phase III record compared to updated WIS record (Station AU2056).

Direction Bin (Azimuth degrees, shoreline relative)	Updated WIS, (1976-1995)	Duck Data (1990-1999)		Phase III WIS Data (1956-1975)	
	Percent Energy of Record	Percent Energy of Record	Absolute Difference from Updated WIS	Percent energy of Record	Absolute Difference from Updated WIS
0-29.9	0.9	0.2	-0.7	3	2.1
30-59.9	5.7	7	1.3	27.1	21.4
60-89.9	40.5	40.8	0.3	39.5	-1
90-119.9	35.0	42.5	7.5	16.2	-18.8
120-149.9	15.4	9.4	-6	11.9	-3.5
150-180	2.5	0.1	-2.4	1.9	-0.6

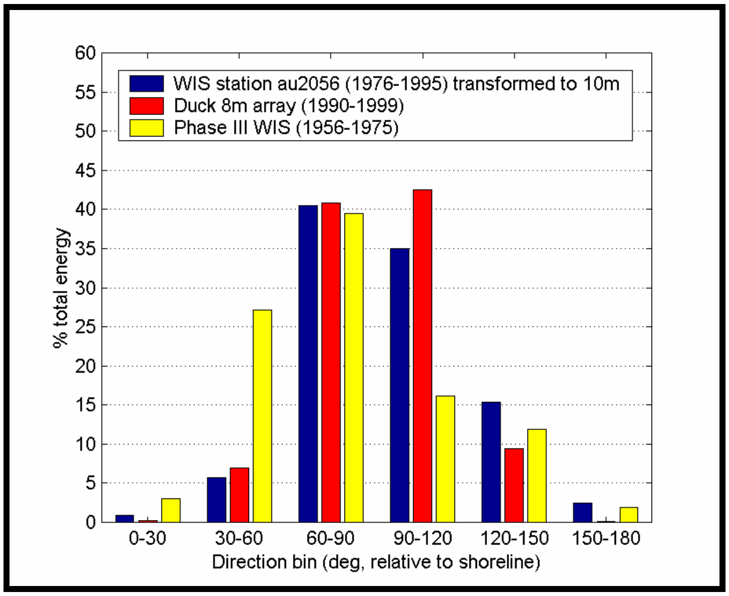

Figure 4-22. Histogram of relative wave energy for wave records divided into six directional bins. Bar length is determined by the product of percent occurrence and squared mean wave height of each directional bin. Directions are relative to approximate shoreline orientation (340°) at Duck, NC (20° on this plot corresponds to 0° true north).

4.2.2.2 Model Comparison with Historical Shoreline Change

To ensure that spectral wave modeling and associated longshore sediment transport potential could be used effectively to evaluate long-term alterations to the littoral system, a comparison of model predictions with observed shoreline change was performed. This analysis provides a semi-quantitative method for determining whether a) wave-induced longshore transport is responsible for observed shoreline change, and b) long-term shoreline change trends are consistent with shorter time-period (20-year) sediment transport potential analyses. For the four potential sand resource areas, an evaluation of model output was performed using a comparison of computed gradients in sediment transport to historical shoreline change data. The basis for this comparison is the relationship between shoreline movement and the longshore gradient of sediment transport. Simply expressed, this relationship is

$$\frac{\partial Q}{\partial y} \propto \frac{\partial x}{\partial t} \tag{4.15}$$

where Q is sediment transport, y is alongshore distance, x is the cross-shore position of the shoreline, and t is time. A comparison of results should illustrate similar trends in long-term shoreline change and transport potential computed using wave conditions that represent long-term average conditions. Good general agreement between these two quantities would suggest that the transport potential model reasonably represents long-term coastal processes for a given area, and thus, the model's ability to predict the likely impacts that would result from offshore dredging.

The time variation in shoreline position was determined from an analysis of historical shoreline data for each of the study areas. Regional change analysis provides a without-project assessment of shoreline response for comparison with predicted changes in wave-energy focusing at the shoreline resulting from potential offshore sand dredging activities. Because continuous measurements of historical shoreline change are available at 50-m alongshore intervals, model results (wave and sediment transport) at discrete intervals along the coast can be compared with historical data to develop process/response relationships for evaluating potential impacts. In this study, shoreline data covering the periods 1849 to 1980 for Dare County, NC were used to quantify trends (see Section 3.1). Methods used for compiling and analyzing historical data sets are described in Byrnes and Hiland (1994). Alongshore variations in sediment transport were determined using the computed values of transport potential for each shoreline for modeled existing conditions. The comparison of shoreline change to the modeled transport gradient for North Carolina is shown in Figure 4-23.

Trends in shoreline change generally agree with modeled transport gradients for the North Carolina coast north of Oregon Inlet (Figure 4-23). Results of both analyses illustrate a stable to erosional shoreline, with an area of maximum erosion between 5 and 7 km north of Oregon Inlet. For the modeled transport gradient, there is an area of accretion approximately 3 km north of the point of maximum erosion that is not indicated in the shoreline change analysis. This may be due to al lack of detailed nearshore bathymetry data for a 2-km section of coastline at this location. Bathymetry data used for developing the model grid was digitized from a NOAA navigational chart and does not have a high level of detail as is available in the data used for adjacent sections of coast. In addition, severe erosion observed immediately north of Oregon Inlet may have created an erosional hot-spot that has propagated to the north as shoreline orientation changed over the past century.

The gradient in sediment transport potential was not expected to simulate this process that likely occurs over a time period spanning several decades. Significant migration of Oregon Inlet also may be responsible for some of the differences between observed and modeled shoreline change trends, where the peak in erosion likely has migrated south with the inlet. Therefore, the peak erosion area determined from the gradient of modeled transport potential, based on 20 years of recent wave information, may be more representative of present conditions than the long-term shoreline change (based on more than 100 years of shoreline data). Overall, good agreement exists between observed shoreline change and longshore gradient in modeled transport potential. Minor differences between the two methods, especially in the region of maximum erosion, likely are due to long-term alterations (spanning several decades) in shoreline position and the historical migration of Oregon Inlet.

4.2.2.3 Significance of Proposed Dredging

The significance of the changes to longshore transport along the modeled shoreline that result from dredging the proposed borrow sites to their maximum design depths was determined using the method outlined in Kelley et al., (2001). For the determination of dredging impact significance, 20 model runs in addition to the 27 existing and post-dredging runs were executed. For this study, 20 one-year periods were run, using the same directional binning as the existing and post-dredging runs. Each one–year period modeled represents a single year of the 20-year WIS hindcast record. Sediment transport potential was computed for each one-year period. The standard deviation of transport potential then was computed at each separate grid node, providing an estimate of the annual variability of the sediment transport climate along the shoreline. This method therefore incorporates the temporal and spatial variability of transport potential along the modeled shoreline.

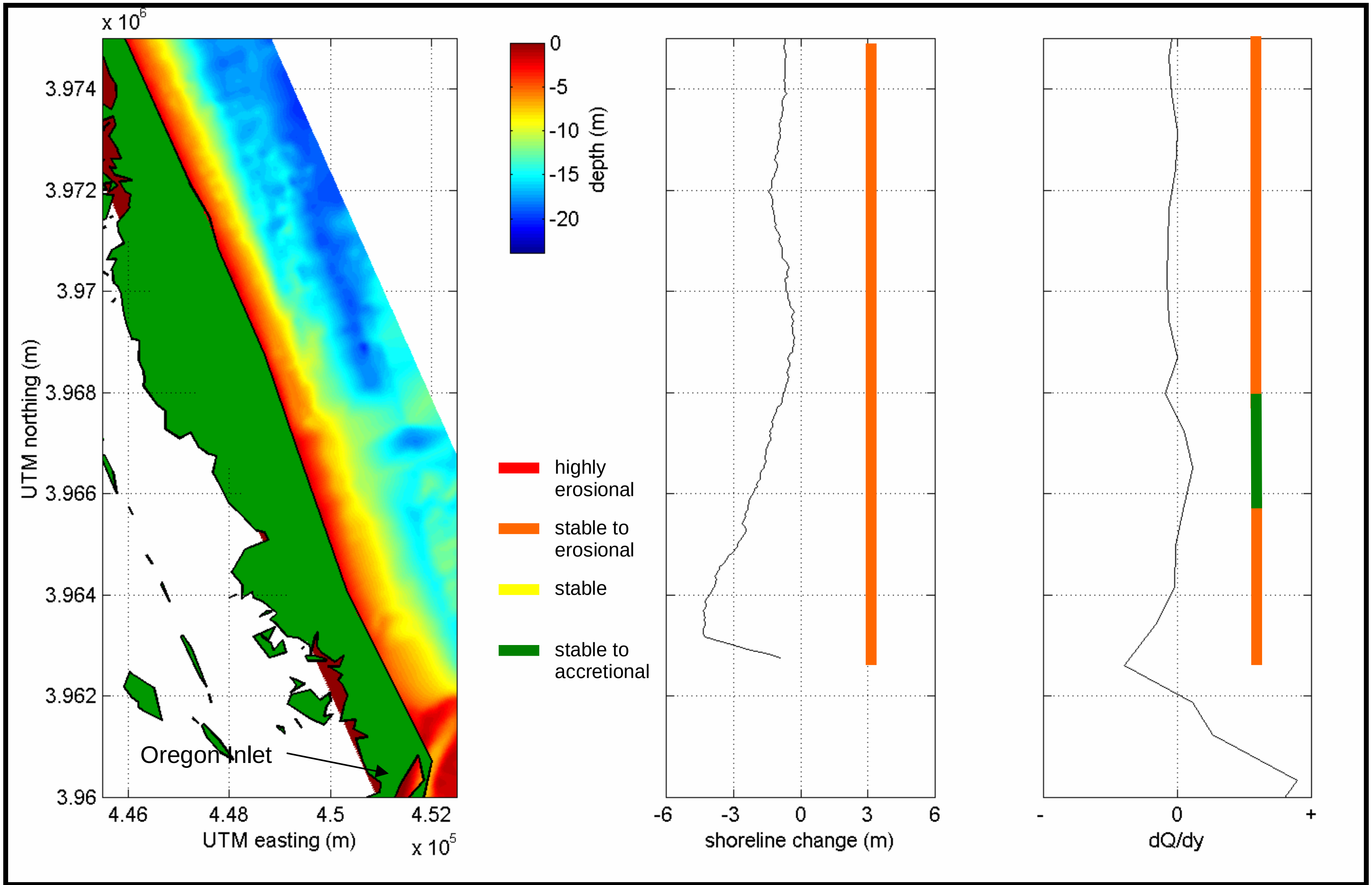

Figure 4-23. Comparison of historical shoreline change and gradient of modeled transport potential (dQ/dy) for the North Carolina shoreline. Color bars indicate whether the shoreline is accretional, stable, or erosional.

The criterion for determining dredging significance is one-half of a standard deviation (±0.5σ) in this case where the 20-year WIS record was run as 20 individual years. This criterion is more restrictive than the ±σ value used in Kelley et al. (2001) for this same coastline because the original significance criterion was computed using the 20-year WIS record split into five four-year periods, which results in a smaller value of the standard deviation. For the North Carolina coastline, the standard deviation computed using five four-year periods is approximately 80% of the standard deviation computed for the same shoreline using 20 one-year periods.

In Figure 4-24, the computed change in transport potential for the two modeled scenarios (where Sites 3 east and 3 west were modeled alternately with Sites 1, 2, and 4) falls within the 0.5σ significance envelope determined for this shoreline. Therefore, according to this analysis, the modeled borrow site configurations are acceptable without any additional stipulations. It is likely that if Sites 3 east and 3 west were dredged simultaneously with the other three sites, the resulting change in computed sediment transport potential would exceed the 0.5σ significance envelope. However, it is estimated that the modeled change would occur well within ±σ, the level where borrow site configuration design would be rejected or modified so that impacts are within acceptable limits. If simulated potential change is greater than ±σ, appropriate mitigation may be required along the adversely affected shoreline to mitigate the impact, such as a redesign of the borrow site configuration. From our analysis, the redesign would likely invlove a reduction in maximum allowable dredged depth at a given site.

4.3 SUMMARY

The wave transformation numerical model STWAVE was used to simulate how wave fields are modified by the bathymetry offshore North Carolina. Wave conditions run in STWAVE were developed using a 20-year WIS wave hindcast for a station offshore Dare County, NC. The same wave conditions were run for existing and post-dredging conditions. Wave model output was then used to determine sediment transport potential along the entire shoreline, for both existing and post-dredging conditions. The alongshore variation of the computed gradient of transport potential was compared to measured shoreline change to ensure that spectral wave modeling and associated longshore sediment transport potential could be used effectively to evaluate long-term alterations to the littoral system

Once the change in sediment transport potential was determined between existing and post-dredging conditions, the significance of these changes was determined by applying a significance criterion based on the natural temporal and spatial variability of sediment transport along the modeled coastline. An additional 20 wave model runs were executed to determine the significance criterion envelope. Each of the 20 runs represented a single year of the 20-year WIS hindcast wave data set. The standard deviation, σ, of sediment transport potential was computed for the entire coastline. The final determination of dredging impact significance was made by comparing actual change in transport potential between existing and post-dredging conditions to a significance envelope of one-half the standard deviation (±0.5σ) along the shoreline (Figure 4-24). It was determined that no significant changes to longshore sediment transport will result from the modeled borrow site configurations, where Sites 3 east and 3 west were modeled separately. If sites were dredged simultaneously, the impacts are estimated to exceed the ±0.5σ, and therefore would require mitigation along the affected shoreline, or a redesign of the borrow site configuration, likely a reduction in maximum design depth at one of the sand borrow sites.

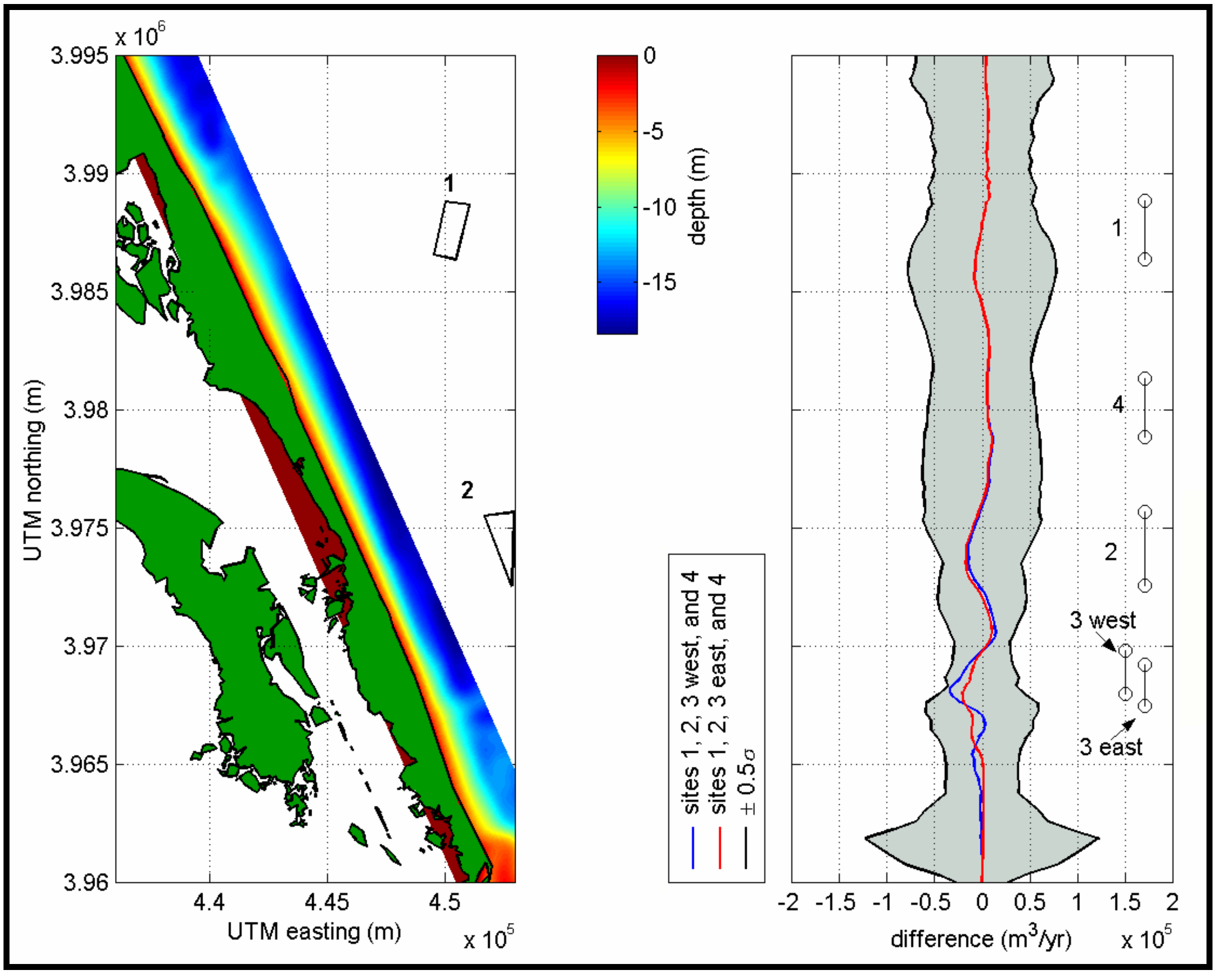

Figure 4-24. Plot of transport potential difference between existing and post-dredging conditions, including the maximum influence envelope.

5.0 CIRCULATION AND OFFSHORE SEDIMENT TRANSPORT DYNAMICS

5.1 CURRENTS AND CIRCULATION

Circulation patterns observed at specific areas within the study region were evaluated within the context of potential offshore sand mining operations. The following discussion uses long-term current measurements obtained during previous studies in the region to provide an understanding of temporal variations of inner shelf circulation (time scales of hours to months). The analyses presented in this section describe circulation characteristics within the study region, including major forcing influences, time scales of variability, and the magnitude of resulting currents. Results from this section were used to provide estimates of sediment transport potential at proposed offshore borrow sites.

5.1.1 Historical Data Analysis

Historical current records for data collected at the FRF in Duck, NC were chosen for detailed analysis of current processes. Current data were collected at two sites; a Marsh-McBirney single point current meter (MMB) at the 8-m depth contour in 5 m of water and an upward looking RD Instruments Acoustic Doppler Current Profiler (ADCP) anchored to the seafloor at the 13-m depth contour. The MMB was positioned at 36°11.30’ N, 75°44.60’ W and recorded data intermittently from April through December 1997. ADCP measurements were obtained from January through December 1997 in approximately one month continuous records at 36°11.39’ N, 75°44.15’ W.

All current data were first rotated from a north/east coordinate system to a cross-shelf/along-shelf coordinate system. This rotation of the coordinate system allowed analysis of currents flowing normal and parallel to the shoreline and nearshore bathymetric contours. The sign convention holds that positive across-shelf flow is directed offshore and negative across-shelf flow is directed onshore. Positive along-shelf flow is directed approximately north-northwest; negative flow is directed approximately south-southeast.

5.1.1.1 Description of Observed Currents

Current measurements at FRF locations throughout the approximate one-year period revealed temporal and spatial variability, but mean flow was southerly, approximately along the inner shelf bathymetric contours. Strongest flow was observed in the along-shelf direction, with peak velocities of nearly 150 cm/sec at the surface and 100 cm/sec near the seabed; maximum currents were directed down-shelf, or to the south (Figure 5-1). Maximum up-shelf (northward) currents occasionally reached 80 cm/sec at the surface. Up-shelf bottom currents never exceeded 40 cm/sec (Figure 5-2). Flow reversals, when currents were directed toward the north then reversed to flow in a southerly direction, were noted frequently.

In the cross-shelf direction, mean flow was oriented onshore at the surface, consistent with upwelling processes that push bottom waters up onto the shelf. Maximum across-shelf flow was 70 cm/sec (directed onshore) at the surface and 30 cm/sec (directed offshore) at the bottom. The counter flow of surface water and near-bottom currents provides evidence of a circulation cell due to upwelling. A more detailed analysis of the current regime at the ADCP location (13 m) was possible following numerical separation of overall measured currents into known physical processes. The MMB data primarily were analyzed for comparison with ADCP current measurements revealed along the inner shelf.

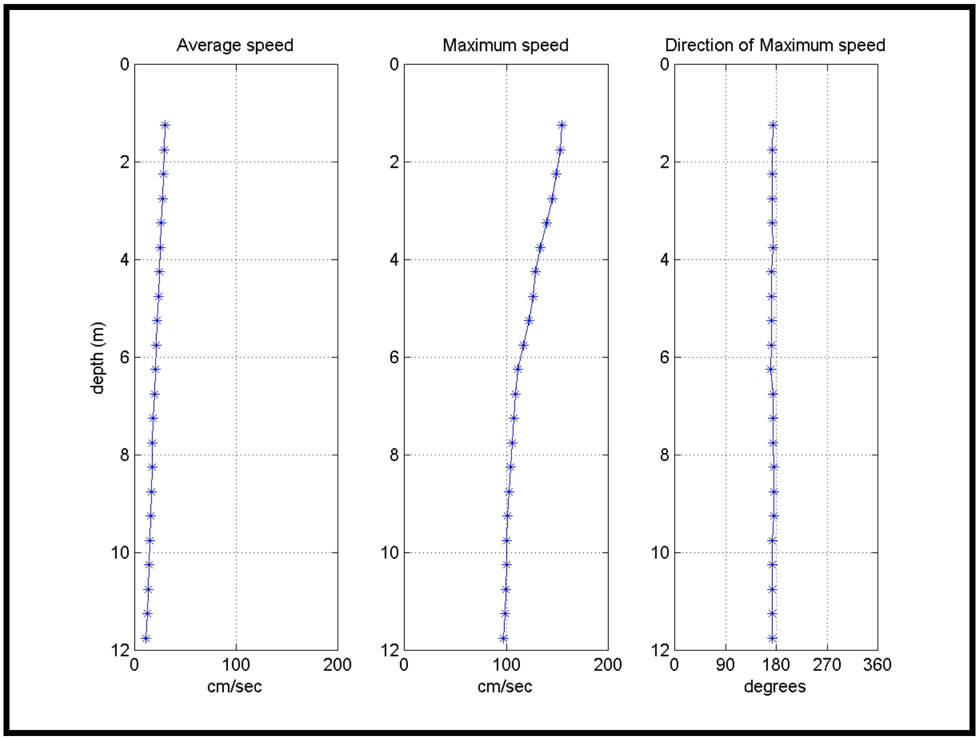

Figure 5-1. Vertical profile of average and maximum current speeds from January through December 1997. Maximum currents were directed southerly at 150 cm/sec (≈ 3 knots) in the upper water column and 100 cm/sec (≈ 2 knots) near bottom.

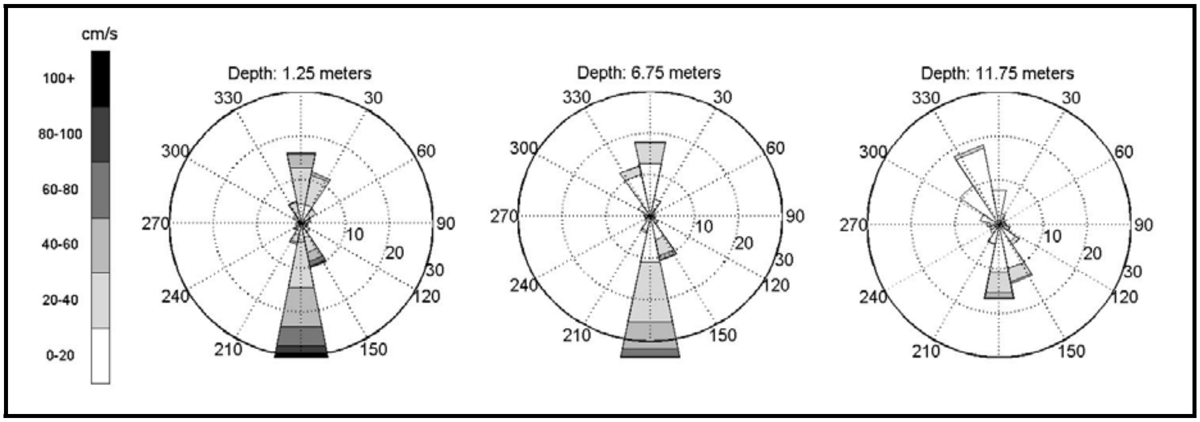

Figure 5-2. Rose diagram of currents measured at the surface (1.25 m), mid-depth (6.75 m), and near-bottom (11.75 m). Rings represent 10%, 20% and 30% occurrence, and shading corresponds to current speed ranges as denoted by the scale.

5.1.1.2 Numerical Decomposition of Historical Current Data

Currents observed along the continental shelf represent the cumulative effects of many different physical processes, each possessing unique time scales and amplitudes. These processes occur simultaneously; hence, the current observed at any one time can be considered the summation, or superposition, of all individual processes. This section describes the numerical procedures used to separate the observed currents into individual subsets, each with specific time scales of variability. This procedure allows analysis of each process to determine their relative importance to total circulation in the region.

Separation of the total signal into specific process components was performed using various numerical analysis techniques, such as tidal harmonic decomposition, as well as the application of a series of low-, band-, and high-pass filters. Results of the numerical separation analysis represent subsets of individual time series. Each subset represents a specific physical process, such as:

- High-frequency currents (non-tidal processes with periods less than approximately 33 hours);
- Tidal currents (diurnal and semi-diurnal constituents);
- Wind-driven currents (1 to 33 day frequency band).

The first step in the separation analysis is to remove tidal currents from the raw data using harmonic analysis. Harmonic analysis calculates the amplitude and phase of 21 individual tidal constituents using a least-squares fit of the constituent sinusoid to the raw data signal. Tidal constituents removed included K1, M2, M4, M6, S2, N2, O1, S4, S6, M8, MK3, MN4, MS4, 2N2, OO1, M1, J1, Q1, 2Q1, L2, and 2SM2. Most constituents represent high-frequency tides, or tides having periods less than approximately 28 hours (diurnal tides).

This analysis produces a separation of total observed currents into two time series: one time series is predicted tides, based on a reconstruction of individual tidal components (the summation of 21 sinusoidal functions), and the second time series is non-tidal or residual currents. Residual currents were generated by subtracting (point by point) the reconstructed tidal time series from the original signal.

The residual signal became the basis for subsequent analyses. The first step in processing was to remove the remaining high-frequency energy. This was accomplished by applying a PL33 low-pass filter over the residual signal. The PL33 is a standard oceanographic filter which uses 1/(33 hours) as the cutoff frequency, and is used primarily to remove tidal energy (or all signal energy with periodicity less than 33 hours) from oceanographic time series. Some energy leakage can occur near the cutoff frequency using this filtering method; however, this effect is minimal because the significant diurnal (and higher frequency) tides had been removed prior to this step. The low-passed time series was termed the subtidal signal.

The subtidal signal was subtracted from the previous residual signal, resulting in a high-frequency time series containing all non-tidal currents having periods less than approximately 33 hours. This high-frequency signal (typically referred to as noise) contained significant energy, which can be due to several sources, including actual flow field turbulence, wave-induced flow, as well as possible data contamination due to mooring motions. The high-frequency signal was saved as a separate time series for later analysis and comparison.

The subtidal signal then was reduced further into distinct frequency bands. The first frequency band was defined as processes with time scales of 1 to 15 days. It was assumed to include wind-driven flows, as well as other processes of similar time scales, such as buoyancy-driven flow from Chesapeake Bay observed by Boicourt (1973). Infragravity motions are included in this frequency band as well, with time scales of approximately 1 to 14 days. These motions have been shown to play a significant but secondary role to cross-shelf currents in this region (Wright et al., 1994). This wind-driven band was expected to yield significant energy (Madsen et al., 1993; Berger et al., 1995; Savidge and Bane, 2001). The signal was derived by high-pass filtering the subtidal signal with a 15-day cutoff, and was termed the wind-driven signal, on the assumption most of the energy within this band results from wind forcing.

The second time band defined frequencies with the periodicity greater than 15 days. It was termed the low-frequency band and includes seasonal and slightly higher frequency processes. This series was derived by subtracting the wind-driven signal from the subtidal signal.

Each time series was extracted in sequential manner from the raw signal to a set of individual process-specific signals, each representing the dominant current occurring at specific time scales. This separation procedure was repeated for each data set. Separating these processes from the whole illustrated the relative contribution of each to total observed circulation at a selected sand borrow site. The signal variance of each resulting time series represents its energy level. Comparing the variance of each process to the total signal variance yields a representation of how much energy the process contributed to the whole.

5.1.1.3 Current Components

Tidal Currents

Cross-shelf tides were predominantly semi-diurnal, dominated by the M_2 lunar semi-diurnal tide. Cross-shelf amplitudes range from a minimum of approximately 3 cm/sec directed onshore to a maximum of 9 cm/sec offshore. Along-shelf tidal currents were as often up-shelf as down-shelf, reaching an amplitude of 13 cm/sec. Tides in the along-shelf direction were mixed diurnal, which is consistent with previous studies (Berger et al., 1995).

The analysis revealed that tidal currents affect cross-shelf flow processes at the surface greater than along-shelf processes, but influence near-bottom tidal current components equally. Although tidal flow possessed a higher fraction of cross-shelf energy in the upper water column measured by the ADCP and the MMB, tides only contained about 5% of the total cross-shelf energy (Figure 5-3). Tides were the least important process in along-shelf and cross-shelf directions.

High-Frequency Currents

High-frequency currents were defined as all non-tidal oscillations having periods less than approximately 33 hours, and can result from flow turbulence, responses to localized wind stress, measurement noise, and other random motions of the water column. In shallow water, high-frequency processes tend to contribute a greater fraction to the overall current energy than in deep water.

The standard deviation of cross-shelf high-frequency currents was about 3 to 4 cm/sec, meaning that at any time, the currents vary typically by 3 to 4 cm/sec. The standard deviation of along-shelf flow was about 4 to 6 cm/sec. High-frequency currents contributed approximately 13% of the total cross-shelf variance, 5% of along-shelf variance at the surface, and 10% of along-shelf variance near-bottom (Figure 5-3). The data reveal some correlation between high-frequency currents and subtidal wind-driven currents, suggesting that these high-frequency currents result from wind stress forcing.

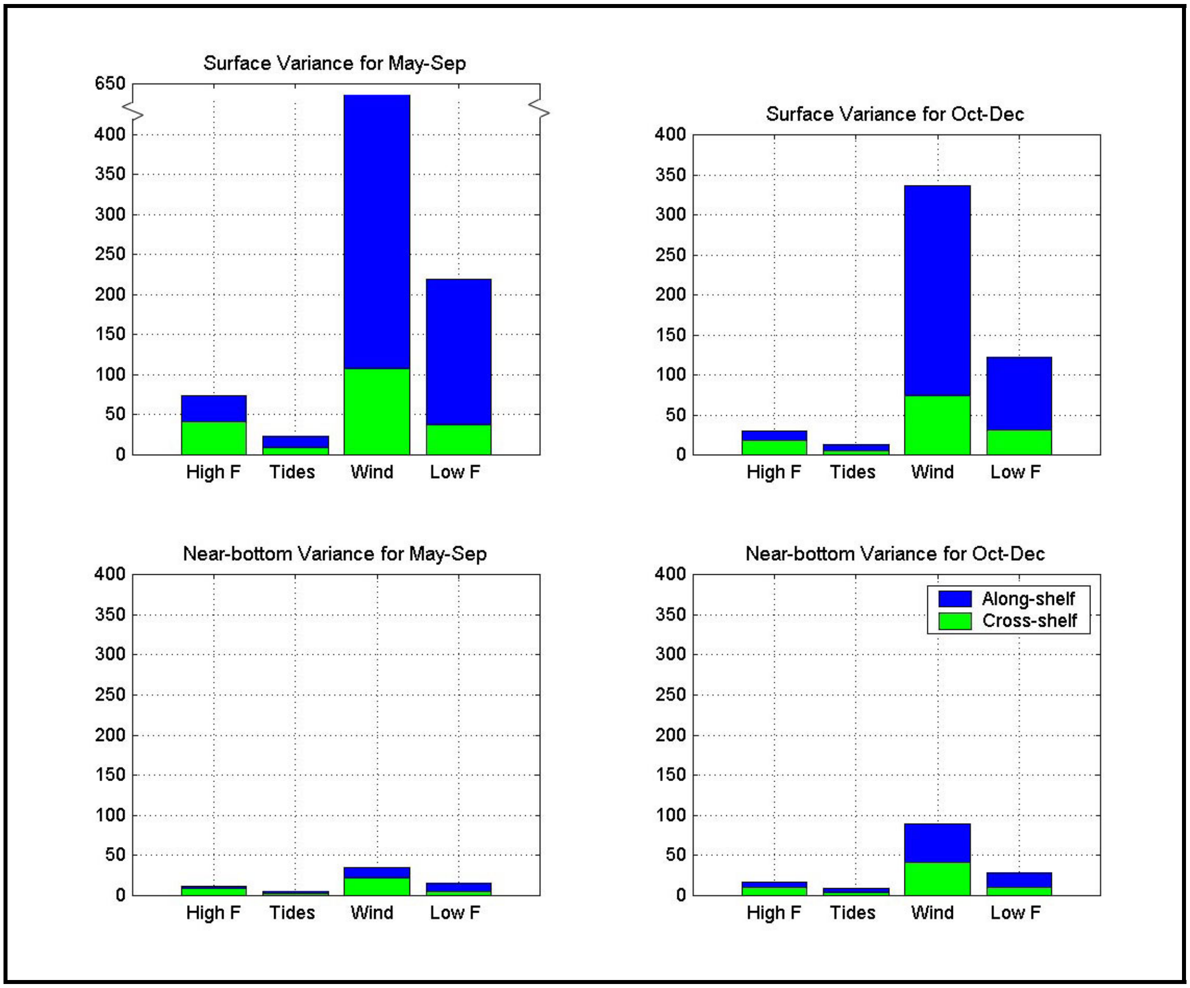

Figure 5-3. Histogram showing the relative energy (variance) of separated current components; high-frequency, tides, wind-driven, and low-frequency flows. Units are $(cm/sec)^2$. Along-shelf wind-driven currents contained the most energy at the surface and near-bottom for both time periods.

Wind-Driven Currents

Wind-driven currents contributed most significantly to the observed currents, containing almost 60% of the total along-shelf current variance (Figure 5-3). At the surface, the along-shelf current variance was more than three times that near the bottom, accounting for as much as 57% of the total energy. Wind-driven currents accounted for approximately 50% of the cross-shelf energy.

The variability of wind-driven along-shelf surface currents during summer months (May to September 1997) is nearly twice the variability of wind-driven surface currents from October to December. Summer surface currents contain more than 10 times the energy of near-bottom currents. This energy gradient indicates a stratification of the water column suitable to upwelling and downwelling events. On the North Carolina shelf, northeast winds are favorable for downwelling (onshore surface flow and offshore bottom flow), and southwest winds produce upwelling (offshore surface flow and onshore bottom flow). From May to September, wind speeds were weaker on average (less than 15 m/s) but more consistent in direction, blowing out of the northeast 20% of the time and out of the southwest 20% of the time (Figure 5-4). In

Figure 5-5, an upwelling event on May 15, 1997 is depicted by a positive cross-shelf surface current and negative near-bottom current in response to a south-southwest wind; along-shelf flow was relatively weak. As wind shifts from south to north, circulation patterns of coastal currents reverse. This is most clearly seen in the downwelling event on May 21 in response to a northeast wind. The southward flowing buoyant coastal plume from Chesapeake Bay is enhanced by northeast winds (Wright et al., 1986). Pulsing winds from May 21 to 23 out of the north-northeast generated strong down-shelf currents reaching 80 cm/s. The inclusion of density-driven processes in the 1 to 15 day frequency band increases the percentage of wind-driven energy in along-shelf currents during summer months.

During winter months (October to December), winds were distributed relatively evenly from southwest clockwise to northeast (Figure 5-4). North-northeast wind speeds occasionally reached 20 m/s. Turbulent mixing has been observed beginning in fall and during winter storms off the coast of North Carolina (Wright et al., 1986). During the strong northeast wind event on October 19, the water column responded relatively uniformly at the surface and near-bottom (Figure 5-6). Offshore-directed currents reach speeds of 30 cm/s, and along-shelf currents flow southerly exceeding 50 cm/s. The strong correlation seen between northeast winds and currents during this event is consistent with the literature regarding wind-driven processes on the North Carolina shelf (Berger et al., 1995). Observations by Savidge and Bane (2001) indicate winds lead transport by half a day or less, and our analysis shows peak wind speeds appear to lead peak currents by approximately 6 hours.

Low-Frequency Currents

Low-frequency currents were not well-resolved because the records were relatively short (i.e., only a few low-frequency cycles were included in each record). Low-frequency values included the mean current. On average, mean flow was southerly in the along-shelf direction, flowing at 15 cm/sec near the surface and 5 cm/sec near the seafloor. Mean cross-shelf currents were positive (directed onshore) throughout the water column during most of the time periods analyzed. Mean cross-shelf flows were approximately 2 to 4 cm/sec, strongest at the surface.

Low-frequency variance ranged from 17 to 21% of the total in the along-shelf direction; low-frequency variance ranged from 12 to 22% in the cross-shelf direction. The variance magnitudes show that low-frequency currents in the along-shelf direction are at least three times more energetic than cross-shelf flow.

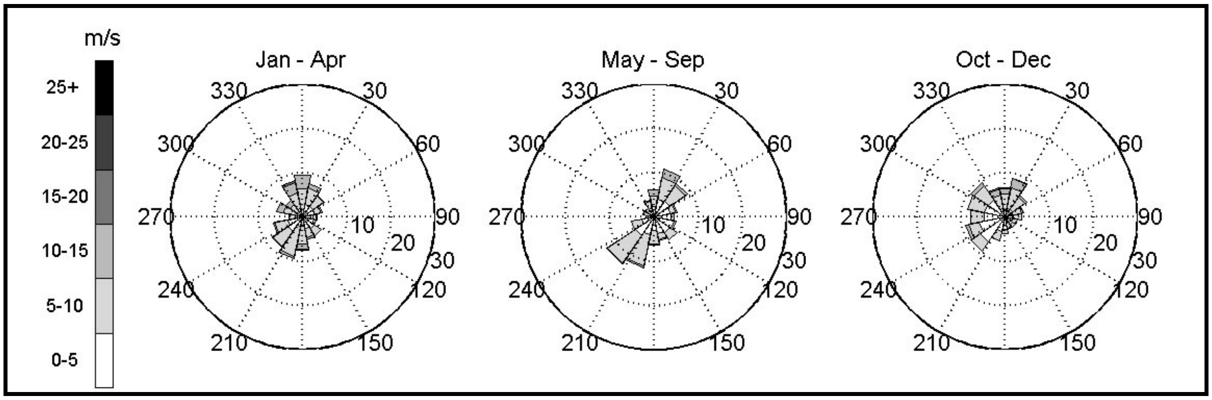

Figure 5-4. Winds measured at the end of the FRF pier in Duck, NC at an elevation of 19.36 m (NGVD) presented in rose diagrams for three time periods.

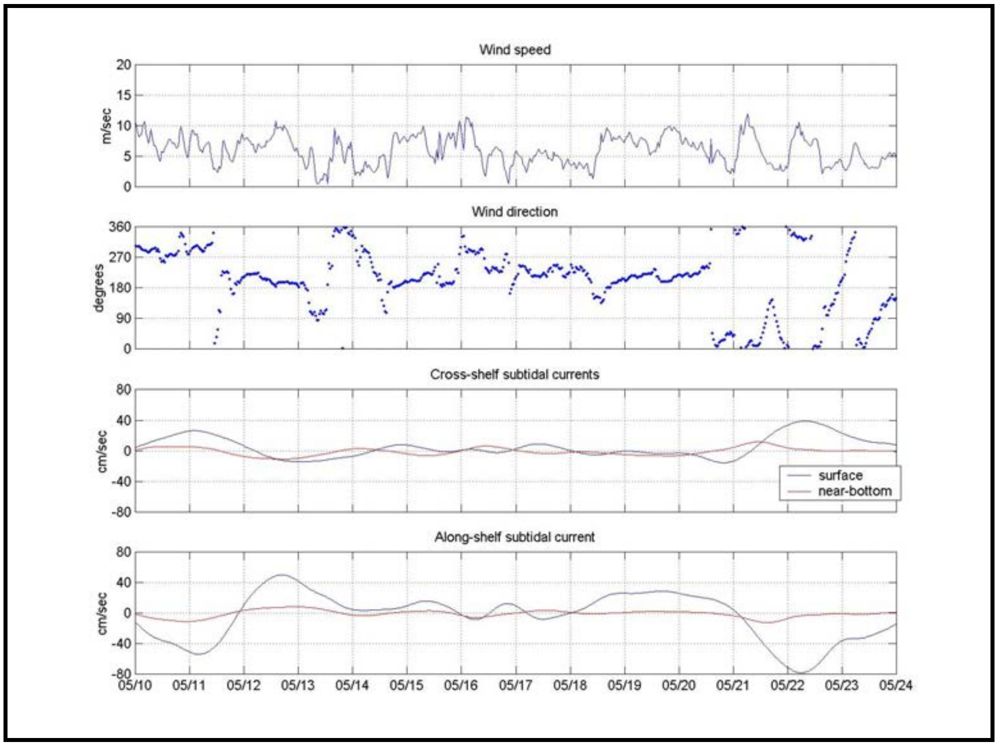

Figure 5-5. Time series of wind speed and direction, and the subtidal component of cross-shelf and along-shelf currents, for a two-week period in May 1997.

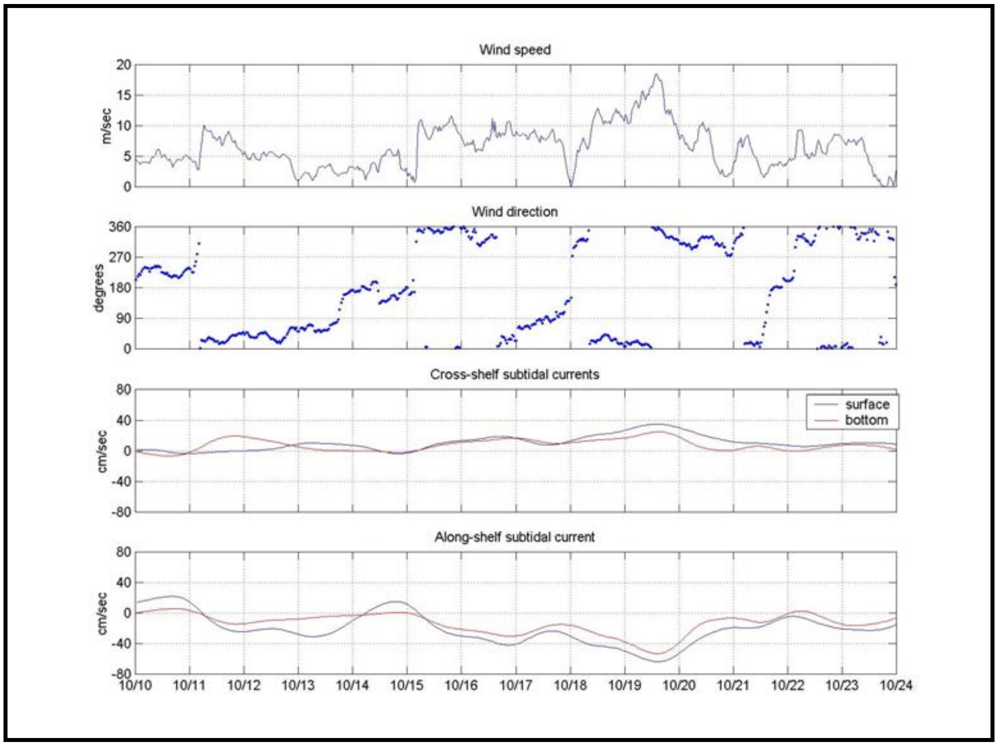

Figure 5-6. Time series of wind speed and direction, and the subtidal component of cross-shelf and along-shelf currents, for a two-week period in October 1997.

5.1.2 Summary of Flow Regimes at Offshore Borrow Sites

The analysis presented above suggests along-shelf currents possess higher energy than cross-shelf flows. The mean along-shelf flow was directed southward. Along-shelf currents were dominated by wind-driven processes, accounting for as much as 60% of the total current energy. Wind-driven flows appeared strongly biased by singular events, either local responses to storm winds, or non-locally generated buoyant flows, that influenced the magnitude of wind-driven current energy.

Although wind-driven currents were less significant in the cross-shelf direction, the largest percentage of cross-shelf energy existed in the wind-driven frequency band. On average, cross-shelf currents were directed offshore. Wave groups and long waves inducing infragravity motions may further contribute to cross-shore current variability. It has been suggested that these motions can be as often onshore as offshore (Wright et al., 1991).

Previous studies indicate that outflow from the Chesapeake Bay exerts significant influence on current patterns in this region (e.g., Beardsley and Boicourt, 1981). Density-driven flows likely dominate along-shelf surface currents during the May to September time period and enhance the effects of upwelling-favorable winds. Currents, which appear dominated by wind-driven processes, would be stronger during time periods of higher wind activity occurring from October to December. In addition to wind-driven currents, high-frequency (noise, random motions) and low-frequency currents also appear to be stronger during winter months (Figure 5-7). This suggests that high- and low-frequency flow processes may be coupled to atmospheric forcing.

Data synthesized in this analysis, and supported by previous studies, suggest that shelf flow is strongest during high-energy wind events, and that near-bottom currents are oriented along the shelf (positive alongshore currents oriented 340°). Wind-driven, near-bottom currents were oriented along-shelf nearly 40% of the time during the two periods analyzed (Figure 5-7). This evidence suggests that singular events, with corresponding higher currents, have the greatest potential to transport sand. If so, sediment transport patterns may be predominately in the along-shelf direction, with a net transport oriented in the direction of mean flow. Based on the variability analysis, low-frequency (mean) flows are predominantly southwestward (Figure 5-7). Data also showed that cross-shelf currents were affected by northeast wind events, driving downwelling during summer months and offshore flow of the uniform water column during fall and winter. Strong wind events forcing near-bottom offshore flows suggest that cross-shelf sediment transport due to currents may be net offshore.

5.2 OFFSHORE SEDIMENT TRANSPORT

Infilling rates for each borrow site were computed based on a method outlined in Madsen (1987), which relies on earlier work described by Grant and Madsen (1986) for wave-current interaction in the bottom boundary layer outside the surf zone.

On the continental shelf, currents are driven by a combination of forces resulting from winds, tides, and atmospheric pressure gradients. Surface waves also create currents on the sea bottom. These wave-induced currents are oscillatory and fluctuate with the passing of each wave. In Grant and Madsen (1986), the interaction of wave-induced currents (high-frequency) and background currents with longer timescales (low-frequency) is modeled. This analysis provides a method for estimating the combined wave-current friction factor (f_{cw}), which is necessary for computing sediment transport at a borrow site.

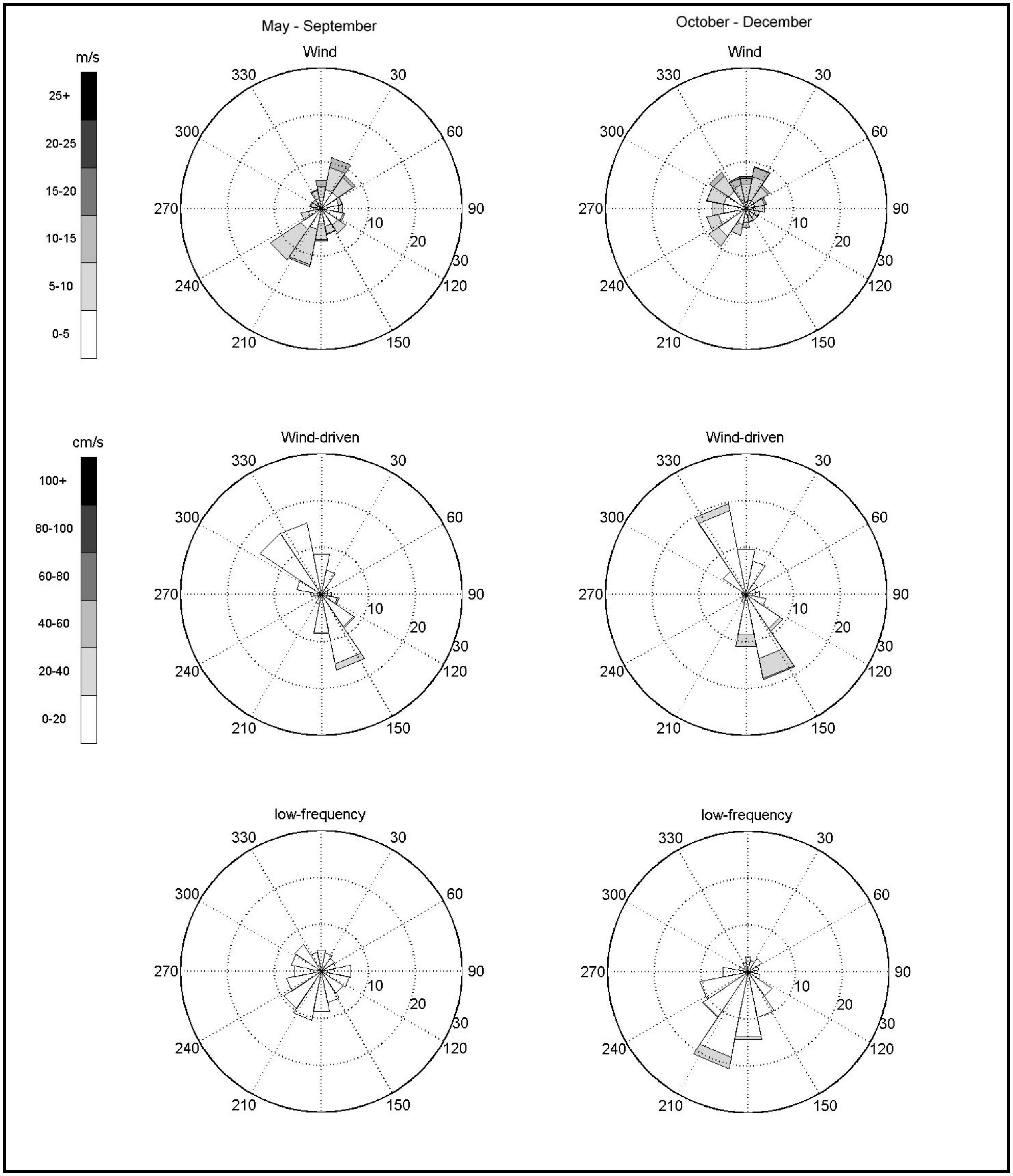

Figure 5-7. Rose diagrams of wind, wind-driven currents, and low-frequency currents during two time periods in 1997: May to September and October to December.

5.2.1 Determining Bottom Transport and Infilling Rates

As outlined in Madsen (1987), the net transport q_{net} at the sea bottom in the presence of waves is computed as the averaged instantaneous transport $q(t)$ over the cycle of a wave period T,

$$q_{net} = \frac{1}{T}\int_0^T q_s(t)dt\,. \tag{5.1}$$

The instantaneous value of sediment transport is computed using a formula given by Madsen (1987) which is based on an earlier empirical relationship known as the Einstein-Brown formula (Brown, 1950) for bottom sediment transport in steady unidirectional flow. The Einstein-Brown relationship gives the dimensionless transport rate ϕ as a function of the Shields parameter Ψ,

$$\phi = 40\Psi^3\,. \tag{5.2}$$

The Shields parameter is used as an indicator of incipient sediment motion, and is the ratio of the shear force τ acting on bottom sediment to the submerged weight of grains. The Shields parameter is expressed as

$$\Psi = \frac{\tau}{(s-1)\rho g d} \tag{5.3}$$

where s is the sediment specific gravity, ρ is the density of water, g is the acceleration of gravity, and d is the sediment grain diameter. The shear stress is a function of the bottom friction factor, f, and the magnitude of the fluid velocity U at the sediment bed. It is expressed as

$$\tau = \frac{1}{2} f \rho U^2\,. \tag{5.4}$$

A critical value for the Shields parameter is determined using the Shields diagram, which defines the point of incipient sediment motion based on the boundary Reynolds number. For instantaneous values of the Shields parameter that are less than the critical value, no sediment motion will occur.

Therefore, during portions of the wave period that sediment motion does occur, the instantaneous dimensional sediment transport rate, expressed in a similar form as equation (5.2) is

$$q(t) = c_q w d \left\{ \frac{0.5\rho f_{cw}\left[u^2(t) + v^2(t)\right]}{(s-1)\rho g d} \right\}^3 \tag{5.5}$$

where w is the fall velocity of sediment, c_q is a constant, f_{cw} is the combined wave-current friction factor, and u and v are the velocity components that result from the combination of high-frequency (wave driven) and low-frequency (atmospheric and tide driven) currents.

A method for computing f_{cw} is given by Madsen (1987), which is essentially an iterative method that modifies the bottom boundary layer based on interaction with waves. Initially, the wave friction factor, $f_{wc,}$ for waves in the presence of currents is determined by using the equation

$$\frac{1}{4\sqrt{f_{wc}/C_\mu}} + \log\frac{1}{4\sqrt{f_{wc}/C_\mu}} = \log\frac{C_\mu u_b}{k_s \omega} - 0.17 \tag{5.6}$$

where k_s is a characteristic bottom roughness, ω is the wave radian frequency ($2\pi/T$), u_b is the magnitude of the velocity under the wave (in linear wave theory $u_b(t)=\sin[kx - \sigma t]$), and the coefficient C_μ is described as

$$C_\mu = \left(1 + 2\mu\cos\theta_c + \mu^2\right)^{1/2} \tag{5.7}$$

where

$$\mu = \left(\frac{u_{*c}}{u_{*wm}}\right)^2 \tag{5.8}$$

and θ_c is the angle between the wave approach and the current direction, u_{*c} is the current shear velocity, and u_{*wm} is the magnitude of the maximum wave shear velocity in the presence of currents. In this procedure, an initial guess for the value of μ must be made, because u_{*wm} is initially not known.

The final value of f_{cw} is computed using the equation

$$f_{cw} = 2\left(\frac{u_{*c}}{u_r}\right)^2 \tag{5.9}$$

where u_{*c} is the current shear velocity, and u_r is the magnitude of the measured current, measured at a particular height above bottom, z_r. The current shear velocity is determined by the equation

$$u_r = \frac{u_{*c}}{\kappa}\left(\ln\frac{z_r}{\delta_{cw}} + \frac{u_{*c}}{u_{*m}}\ln\frac{\delta_{cw}}{z_0}\right) \text{; for } z_r > \delta_{cw} \tag{5.10}$$

which is quadratic in u_{*c}, and

$$u_{*wm}^2 = \frac{1}{2} f_{wc} u_b^2, \tag{5.11}$$

$$u_{*m}^2 = C_\mu u_{*wm}^2, \tag{5.12}$$

$$\delta_{cw} = \frac{\kappa u_{*m}}{\omega}, \tag{5.13}$$

where,

u_{*wm} = magnitude of the maximum wave shear velocity in the presence of currents,

f_{wc} = wave friction factor, for waves in the presence of currents,
u_{*m} = combined wave-current shear velocity,
δ_{cw} = wave bottom boundary layer thickness,
u_{*m} = combined wave-current shear velocity, and
κ = von Karman's constant (=0.4).

A computer program was developed using the relationships of Grant and Madsen (1986) for the purpose of computing infilling rates at a borrow site. This program uses wave model output (Section 4.0) with current data to determine bottom sediment transport potential at the perimeter of the borrow site and a resulting annualized volume rate of sediment that will enter the borrow site.

5.2.2 Model Input Data

Wave data from STWAVE model runs and ADCP current data collected offshore the FRF provided input conditions for determining borrow site infilling rates. Wave data were extracted from the nine existing condition model runs at the perimeter nodes of each borrow site. These are the same STWAVE model runs used to determine sediment transport potential at the coastline (Section 4.0). Wave model input conditions are listed in Table 5-1. A year-long ADCP current record, collected in 13 m water depth, provided direction and magnitude data at the ocean surface. Currents were binned by eight compass sectors for input to the bottom transport potential model. A listing of surface current inputs used to determine infilling rates is provided in Table 5-2.

In addition to wave and current inputs, other data and parameters were specified for each bottom transport potential model run performed for each borrow site. Depths at each perimeter node were taken from the wave model grid. Bottom sediment characteristic grain sizes (d_{90} and d_{50}) also were specified individually for each site. Parameters used for the model runs at each borrow site are listed in Table 5-3.

Table 5-1. Wave model input conditions used to compute offshore sediment transport potential. STWAVE model output, from each modeled condition, and at each borrow site perimeter grid node was used as input into wave-current interaction model used to determine bottom sediment transport potential.

Wave Period Band	Direction Bin (grid relative)	Peak Wave Direction, θ_p (deg. true north)	H_{mo} Wave Height (m)	Mean Wave Period, T_p (sec)	Percent Occurrence
Band 1	0 to 30	1	1.1	5.1	9.4
	30 to 60	21	1.9	6.0	8.1
	60 to 90	56	1.5	6.7	8.7
	90 to 120	86	1.2	7.4	10.1
	120 to 150	106	0.9	7.6	16.3
	150 to 180	131	0.6	4.6	8.1
Band 2	60 to 90	66	1.9	11.5	6.0
	90 to 120	71	1.5	12.8	19.2
	120 to 150	101	1.3	11.3	6.3

Table 5-2. Surface currents used for modeling bottom sediment transport and the determination of borrow site infilling rates. Current data from Duck FRF 13 m ADCP, using one-year record from Jan 1997 to Jan 1998.

Compass Sector	Current Magnitude (cm/sec)	Mean Current Direction (deg. true north)	Percent Occurrence
337.5 to 22.5	26.6	3.6	26.5
22.5 to 67.5	19.2	38.9	9.6
67.5 to 112.5	11.6	88.8	3.2
112.5 to 157.5	14.7	140.6	6.1
157.5 to 202.5	41.7	175.5	43.3
202.5 to 247.5	14.3	219.4	4.2
247.5 to 292.5	9.8	269.1	2.4
292.5 to 337.5	15.2	320.3	4.6

Table 5-3. Borrow site characteristic depths and bottom sediment grain sizes used as bottom sediment transport potential model input.

Borrow Site	Average Bottom Depth (m)	Bottom Sediment d_{90} (mm)	Bottom Sediment d_{50} (mm)
1	17.6	0.85	0.41
2	16.4	0.90	0.38
3 east	20.0	0.42	0.21
3 west	18.7	0.45	0.27
4	20.2	0.83	0.36

5.2.3 Infilling Model Results

Infilling rates computed for each of the five North Carolina borrow sites represent the total potential transport magnitude into each of the sites (Table 5-4). These results likely represent an upper bound for sediment transport at each site. Site 2 has the greatest infilling volume rate, which is the result of a combination of factors, including its shallow depth relative to the other sites and its large perimeter. Because the site is in relatively shallow water, wave-induced currents and background currents are large and more sediment is mobile in the proximity of the borrow site. Sites that have a larger perimeter generally will trap more sediment over a given period. Site 3 east has an infilling rate that is similar to Site 4, even though the area at Site 3 is approximately 70% larger. However, Site 3 is located in slightly deeper water.

Total infilling times presented in the last column of Table 5-4 were computed using the total design excavated volume divided by the computed infilling rates, and therefore represent the length of time required to fill a site that is excavated to the total design depth during a single dredging event. Site 1 has the longest total infilling time, resulting from the large volume extracted from this site and the moderate infilling volume rate. Site 3 west has the shortest infilling time due to its small excavation volume, even though it has the smallest infilling rate of all five sites.

Table 5-4. Characteristic dimensions, computed borrow site infilling rates, and estimated time to fill based on total proposed excavated volume.

Borrow Site	Site Perimeter (m^2)	Excavated Volume (MCM)	Average Perimeter Depth (m)	Annualized Infilling Volume (m^3/yr)	Computed Infilling Time (yr)
1	2.4×10^6	7.2	17.6	73,150	98
2	2.0×10^6	5.8	16.4	123,160	47
3 east	0.7×10^6	1.4	20.0	38,270	37
3 west	0.8×10^6	2.5	18.7	45,970	54
4	1.2×10^6	2.3	20.2	38,420	60

6.0 BIOLOGICAL FIELD SURVEYS

6.1 BACKGROUND

Two field surveys for biological characterization provided environmental data in and around four sand resource areas offshore North Carolina. The surveys were conducted in May and September 1998. Infaunal, epifaunal, demersal fish, and sediment grain size samples, sediment profile images (SPIs), and water column data were collected. The following sections provide the methods, results, and discussion for the biological field surveys.

Sample types and numbers for the May 1998 Survey 1 and September 1998 Survey 2 are summarized in Table 6-1. Sampling locations are illustrated in Figures 6-1 through 6-5.

6.2 METHODS

6.2.1 Survey Design

The primary objective of the North Carolina field surveys in May and September 1998 was to characterize benthic ecological conditions (i.e., infauna, sediment grain size, and epifauna) in four sand resource areas (Figure 6-1). Supporting data collected in the areas consisted of water column profiles. A secondary objective was to obtain descriptive data on infauna and sediment grain size in adjacent areas.

The total numbers of samples by type that originally were proposed for Surveys 1 and 2 were as follows:

Sample Type	Survey 1 (May 1998)	Survey 2 (Sep 1998)
Infauna		
Sediment Profiling Camera	50 stations (2 images/station)	25 stations (2 images/station)
Smith-McIntyre Grab	20 stations (1 grab/station)	50 stations (1 grab/station)
Sediment Grain Size		
Smith-McIntyre Grab	20 stations (1 grab/station)	50 stations (1 grab/station)
Epifauna		
Mongoose Trawls	4 transects (1 transect/area)	4 transects (1 transect/area)
Water Column		
Hydrolab Profiles	4 stations (1 station/area)	4 stations (1 station/area)

The following sampling rationale pertains to Survey 1 in May 1998 and Survey 2 in September 1998. The sampling plan for Surveys 1 and 2 is summarized in Table 6-1. This table lists the surface areas, water depths, and numbers of stations by sample type for each of the sand resource areas and adjacent stations.

Table 6-1. Sampling plan for the North Carolina May 1998 Survey 1 and September 1998 Survey 2.

Sand Resource Area (1,2,3,4)/ Adjacent Station (R1, R2)	Surface Area (million sq ft) and Percent of Total	Water Depth (m)	Number of Stations									
			Sediment Profiling Camera		Smith-McIntyre Grab				Epifaunal Trawls		Hydrolab	
					Grain Size		Infauna					
			Survey 1	Survey 2	Survey 1	Survey 2	Survey 1	Survey 2	Survey 1	Survey 2	Survey 1	Survey 2
1	558 42%	15-24	20	11	8	20	8	20	1	1	1	1
2	153 11%	13-22	5	2	2	5	2	5	1	1+1=2	1	1+1=2
3	367 27%	16-24	13	7	5	13	5	13	1	1	1	1
4	260 20%	16-24	10	3	3	10	3	10	1	1	1	1
R1		24	1	1	1	1	1	1	0	0	0	0
R2		22	1	1	1	1	1	1	0	0	0	0
Total Number of Stations			48 + 2 = 50	23 + 2 = 25	18 + 2 = 20	48 + 2 = 50	18 + 2 = 20	48 + 2 = 50	4	5	4	5

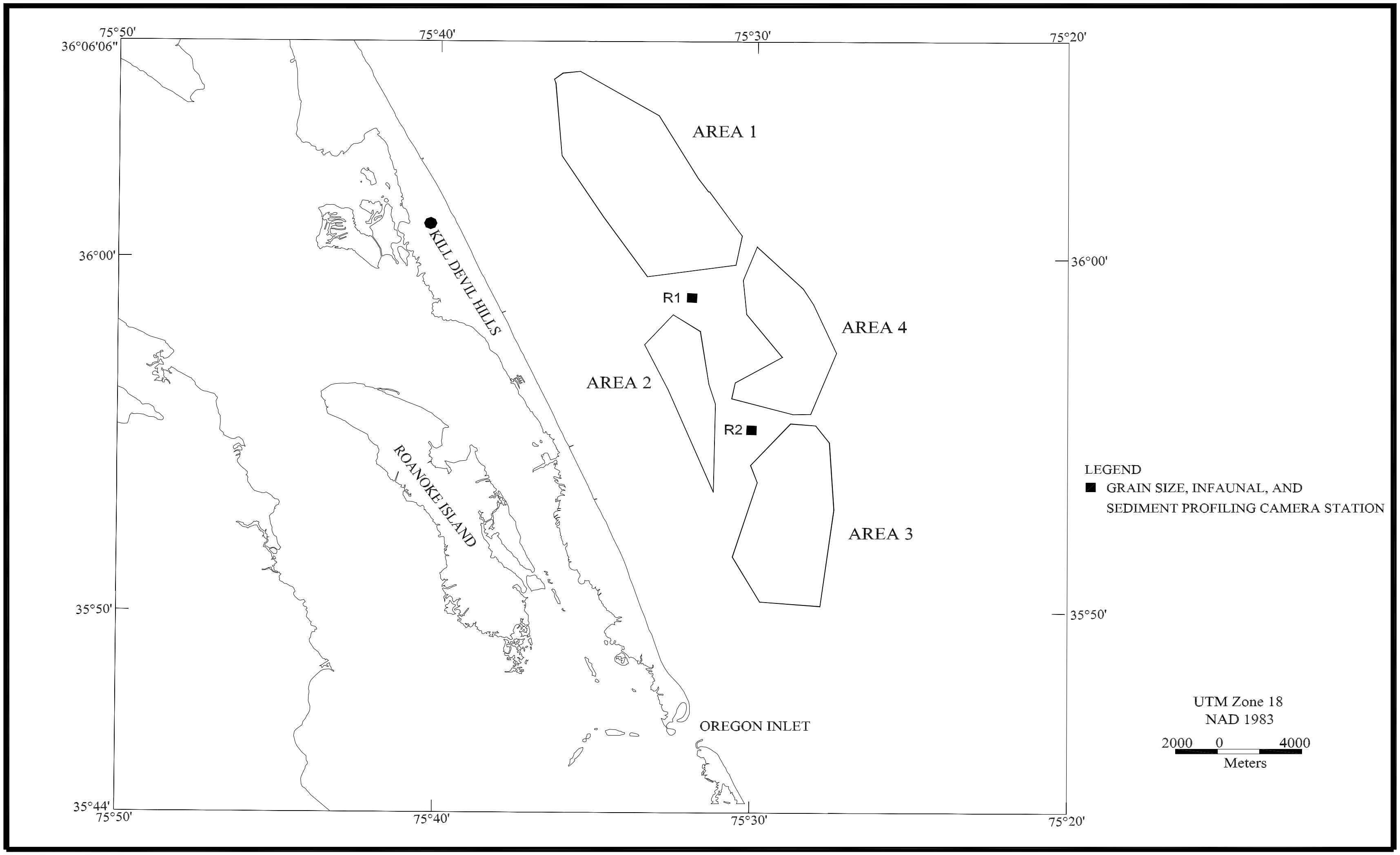

Figure 6-1. Sampling locations for Adjacent Stations R1 and R2 relative to the four sand resource areas and the North Carolina coast.

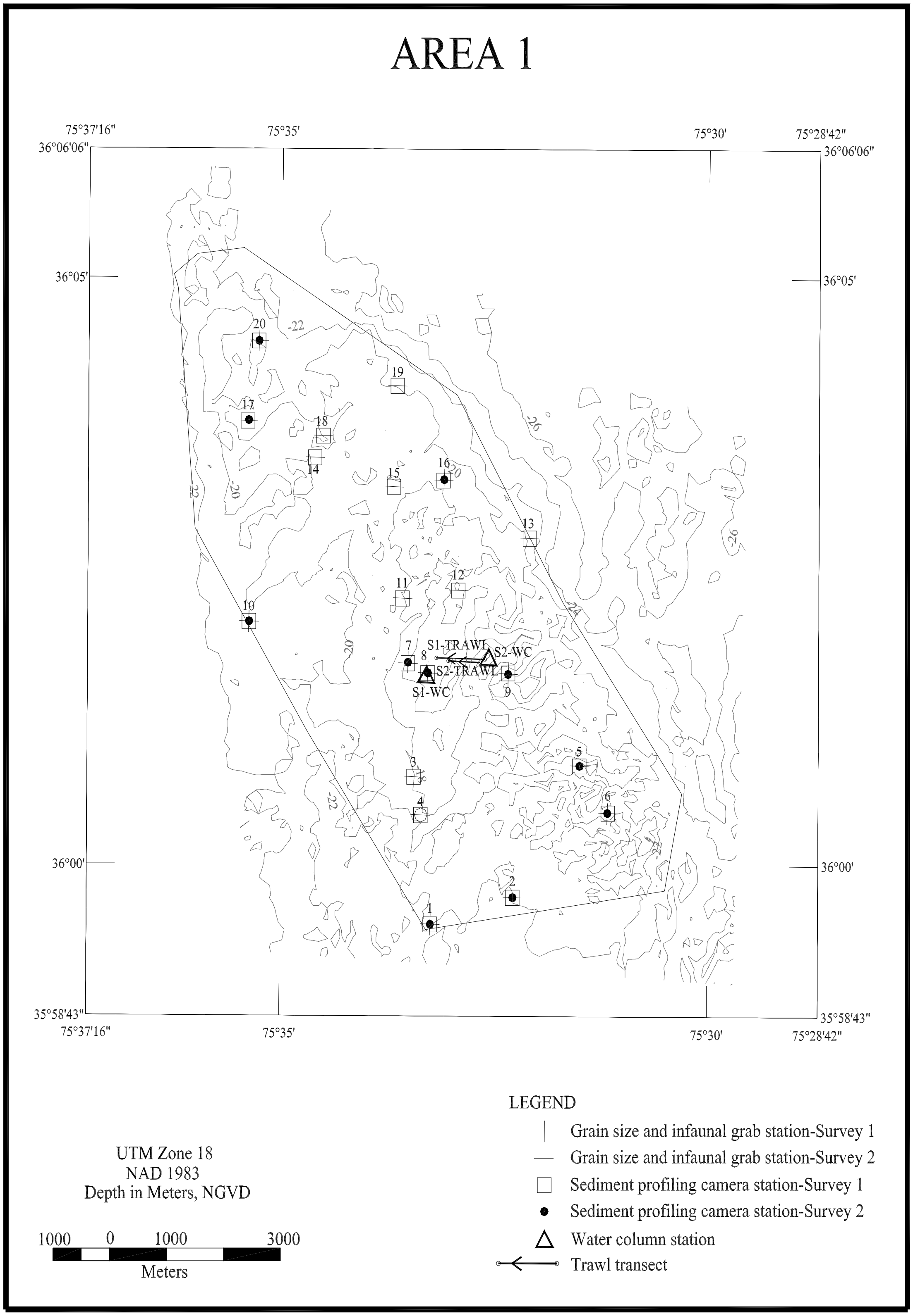

Figure 6-2. Sampling locations for North Carolina Sand Resource Area 1.

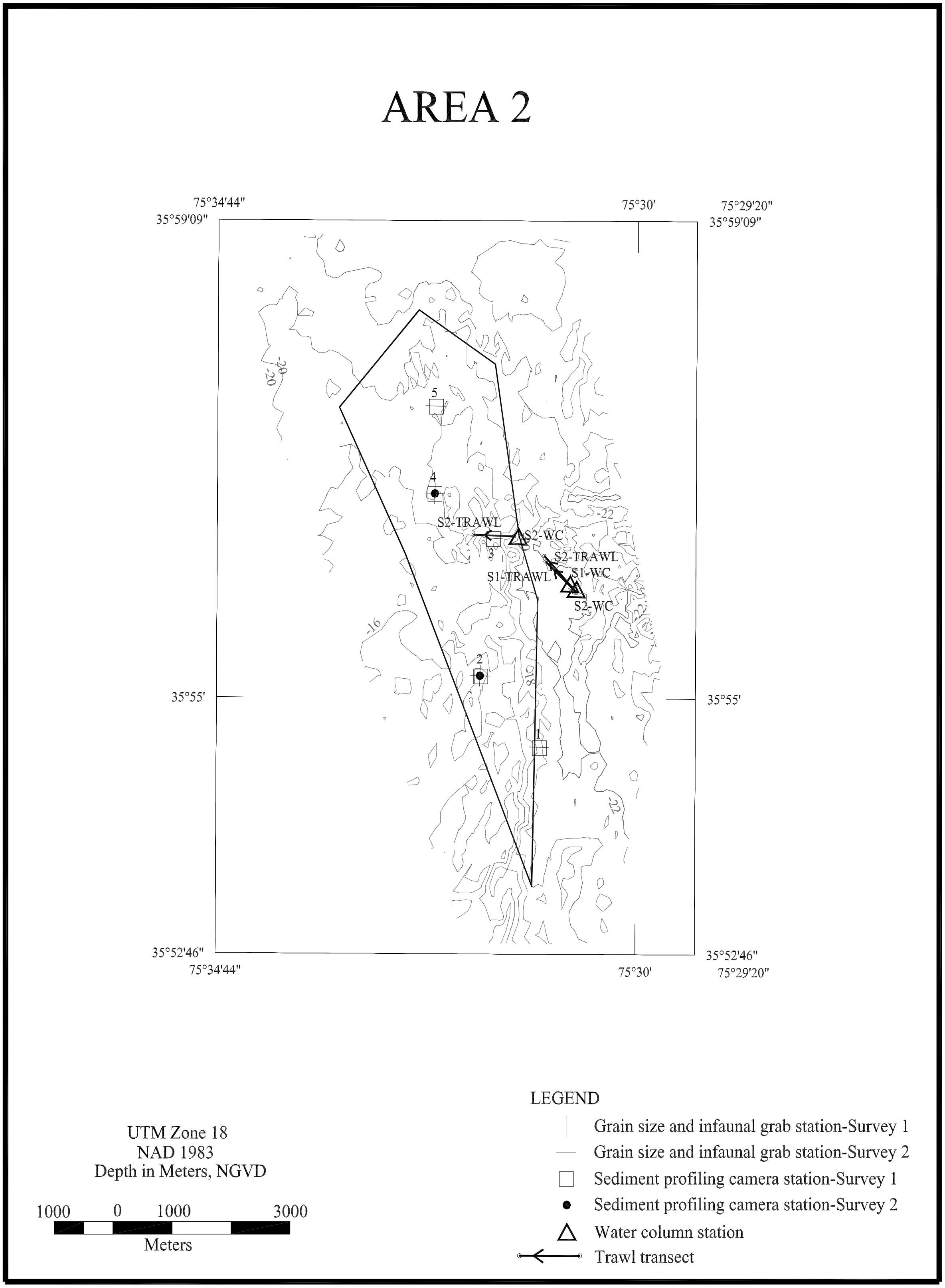

Figure 6-3. Sampling locations for North Carolina Sand Resource Area 2.

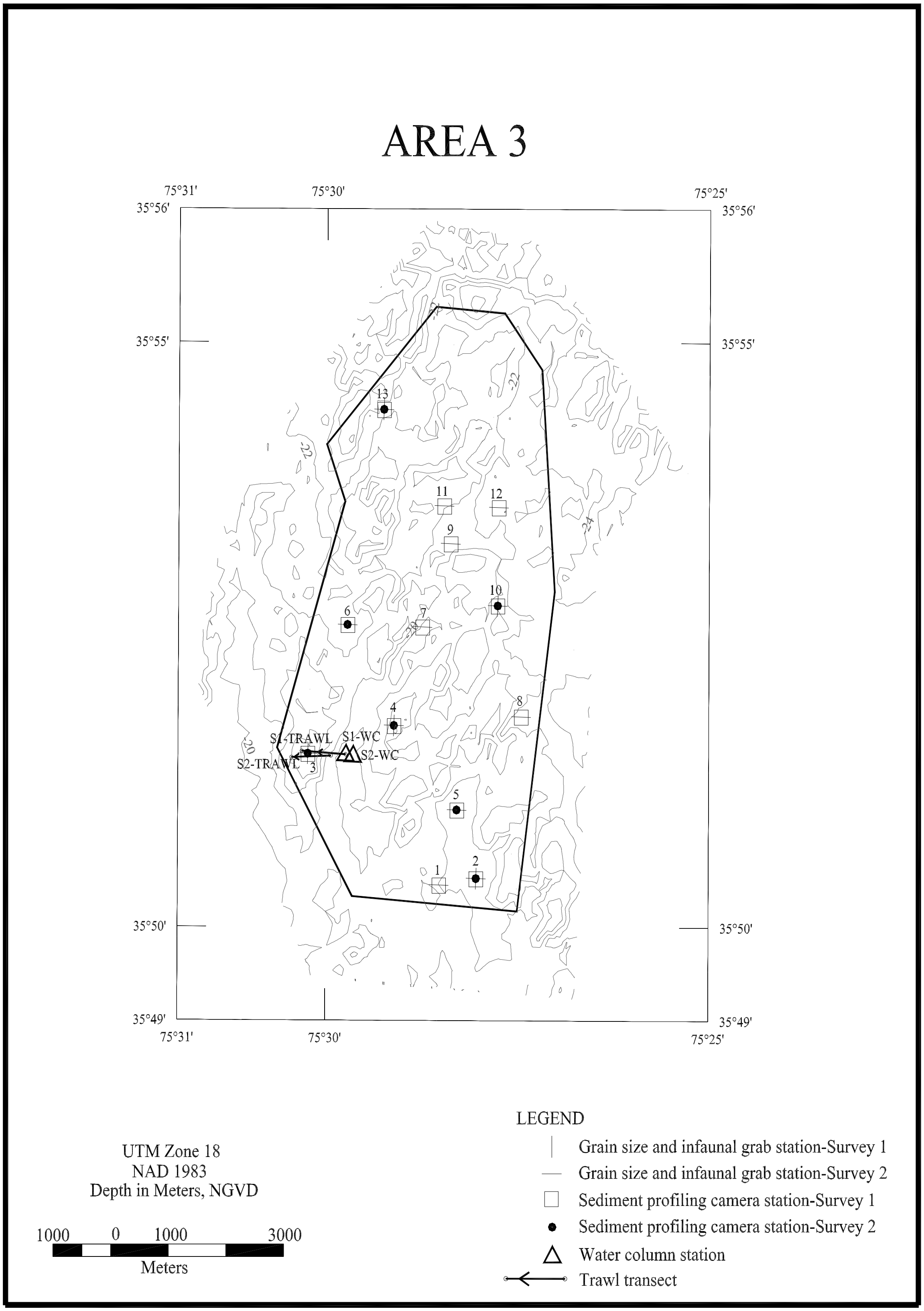

Figure 6-4. Sampling locations for North Carolina Sand Resource Area 3.

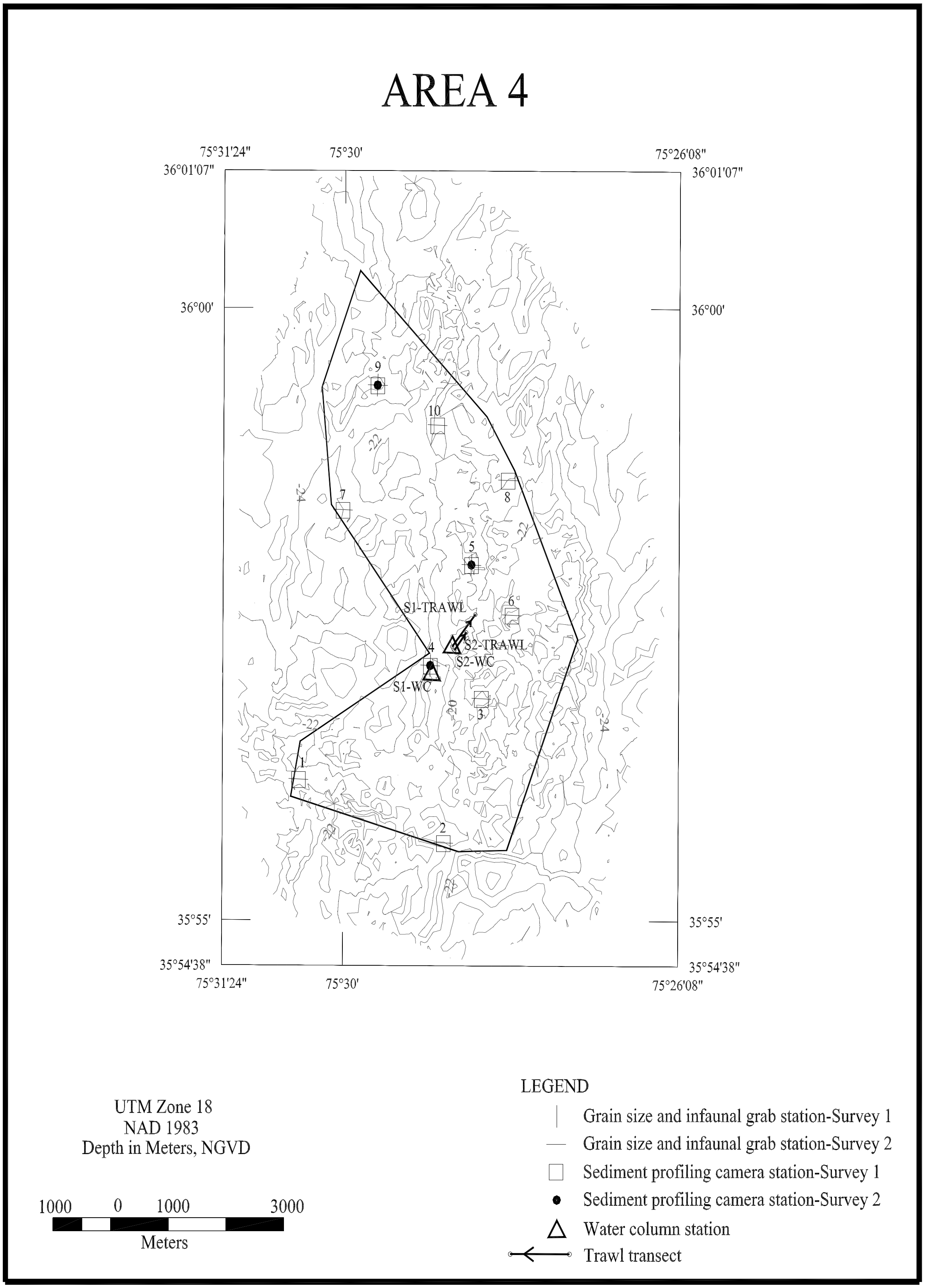

Figure 6-5. Sampling locations for North Carolina Sand Resource Area 4.

6.2.1.1 Infauna and Sediment Grain Size

Survey 1 (May 1998)

To determine the number of infaunal and sediment samples to collect in each area during the May 1998 Survey 1, the surface area and percent of the total surface area for each of the sand resource areas were calculated (Table 6-1). The percent of the total surface area for each of the sand resource areas then was multiplied by the total number of stations originally proposed for the project, resulting in the number of samples per sand resource area.

The next step was to determine the placement of the infaunal (sediment profiling camera and Smith-McIntyre grab) and sediment grain size stations within each area to characterize existing assemblages. The goal in placement of the sediment profiling camera stations was to provide broad spatial and depth coverage within the sand resource areas and, at the same time, ensure that the samples would be independent of one another to satisfy statistical assumptions. To accomplish this goal, a systematic sampling approach was used to provide broad spatial and depth coverage of the target populations. This approach can, in many cases, yield more accurate estimates of the mean than simple random sampling (Gilbert, 1987). Grids were placed over figures of each sand resource area. The number of grid cells was determined by the number of samples per area. One sampling station then was randomly placed within each grid cell of each sand resource area. Randomizing within grid cells eliminates biases that could be introduced by unknown spatial periodicities in a sampling area.

This systematic sampling approach resulted in designation of 50 locations (48 in the 4 sand resource areas plus one at each of 2 adjacent stations) for the sediment profiling camera stations. All station locations then were pre-plotted on geodetically corrected maps.

Attention then was directed to selection of areas for infaunal and sediment grain size sampling using a Smith-McIntyre grab. Whereas 50 stations were proposed for sediment profiling camera sampling, 20 stations were proposed for infaunal and sediment grain size sampling using a Smith-McIntyre grab. Because the purpose of the grab samples was to maximize interpretation of the sediment profiling camera data, it was desirable to collect the grab samples at the same stations as the sediment profiling camera. Maps of the sand resource areas with the 50 sediment profiling camera stations were analyzed and 20 stations were selected (18 in the 4 sand resource areas plus one at each of 2 adjacent stations). Due to the limited number of grabs per area, grab stations were manually selected to maximize spatial, depth, and habitat considerations.

Survey 2 (September 1998)

Placement of infaunal and sediment grain size stations for the September 1998 Survey 2 was determined based on post-plots and results of the infaunal and sediment grain size stations actually sampled during the May 1998 Survey 1. The rationale originally was to sample previously sampled stations for seasonal comparisons during future analyses, and further investigate areas of heterogeneity. With the disturbance to the sand resource areas from Hurricane Bonnie during late August 1998, resampling of previously sampled stations became a priority to attempt detection of storm effects.

For Survey 2, 25 sediment profiling camera stations were proposed. Twenty of these sediment profiling camera stations occupied the same locations as the 20 Smith-McIntyre infaunal stations during Survey 1 because these stations were originally selected to maximize spatial, depth, and habitat considerations. The remaining 5 of the 25 sediment profiling camera stations were located to further characterize areas of heterogeneity (Stations 2, 5, and 17 in Sand Resource Area 1, and Stations 5 and 6 in Area 3).

During Survey 2, 50 Smith-McIntyre infaunal stations and 50 Smith-McIntyre sediment grain size stations also were sampled. The locations of the 50 Smith-McIntyre infaunal stations and 50 Smith-McIntyre sediment grain size stations were identical to each other so that resulting grain size data could be used to interpret the infaunal data. These 50 Smith-McIntyre stations for Survey 2 were in the same locations as the 50 sediment profiling camera stations for Survey 1 to enable comparisons between the May and September data.

6.2.1.2 Epifauna

Trawls were towed to cover as wide a depth range within a sand resource area as possible within the limits of the length of a trawl tow. During Survey 1, one trawl transect was to be made in each of the four sand source areas. This was accomplished for all of the areas except Sand Resource Area 2. During Survey 1, the trawl for Area 2 was taken just outside the perimeter of Area 2. During Survey 2 in September 1998, a trawl transect was made along a line that was close to the line of Area 2 during Survey 1 in May 1998 for comparative purposes. In addition, a trawl was taken inside the boundaries of Area 2.

6.2.1.3 Water Column

A water column profile was made at the beginning point of each trawl transect prior to actual trawling. Parameters measured were temperature, salinity, dissolved oxygen, and depth. When survey results are discussed later, the terms “(in)” and “(out)” are used to distinguish whether the trawl and water column profiles were taken inside or outside of Area 2, for reasons stated in the preceding paragraph.

6.2.2 Field Methods

6.2.2.1 Vessel

The May and September field surveys were conducted aboard the R/V WEATHERBIRD based in Beaufort, NC. The May field survey took place from 27 to 30 May 1998, and the September field survey took place from 14 to 16 September 1998.

6.2.2.2 Navigation

A differential global positioning system (DGPS) was used to navigate the survey vessels to all sampling stations. The DGPS was connected to an on-board computer equipped with Hypack Navigation Software Version 6.4 (Coastal Oceanographics, 1996). With this system, ship position was displayed in real-time on a monitor affixed to a counter top in the wheel house. All sampling stations were pre-plotted and stored in the Hypack program. While in the field, the actual positions of all samples collected were recorded and stored by the program.

6.2.2.3 Water Column

Temperature, salinity, dissolved oxygen, and depth were measured with a portable Hydrolab unit. The Hydrolab was calibrated as needed each working day. Hydrolab measurements of temperature (°C), salinity (ppt), and dissolved oxygen (mg/L) were taken at 1.5-m intervals from the surface to bottom. The Hydrolab was fastened to a weighted line then lowered to depth by hand. All measurements were recorded on standard data sheets.

6.2.2.4 Sediment Grain Size

One grab sample was taken with a Smith-McIntyre grab at each pre-plotted sediment sampling station. Once a sample was deemed acceptable (i.e., adequate penetration and undisturbed surface layer), a sub-sample of sediment (about 250 g) was removed with a 5-cm diameter acrylic core tube and placed in a labeled plastic bag for grain size analyses. This sample was stored at 4°C (i.e., on ice).

6.2.2.5 Sediment Profiling Camera

Two replicate images were taken at each pre-plotted station; each SPI replicate is identified by the time recorded on the film and on disk along with vessel position. Even though multiple images were taken at each location, each image was assigned a unique frame number by the data logger and cross-checked with the time stamp in the navigational system's computer data file. Redundant sample logs were kept by the field crew. At the beginning of each survey day, the time on the camera's internal data logger was synchronized with the internal clock on the computerized navigation system being used to conduct the survey.

Test exposures were fired on deck at the beginning and end of each roll of film to verify that all internal electronic systems were working to design specifications and to provide a color standard against which final film emulsion could be checked for proper color balance. After deployment of the camera at each station, the frame counter was checked to make sure that the requisite number of replicates had been taken. In addition, a prism penetration depth indicator on the camera frame was checked to verify that the optical prism had actually penetrated the bottom to a sufficient depth to acquire a profile image. If images were missed (frame counter indicator), additional replicates were taken. Because of the paucity of fine-grained sediments in the study area, all available prism weights (total of 114 kg) were kept in the camera for the entire survey to maximize the camera's prism penetration.

6.2.2.6 Infauna

One grab sample was taken with a Smith-McIntyre grab at each pre-plotted sediment sampling station. Once a sample was deemed acceptable (i.e., adequate penetration and undisturbed surface layer), a sub-sample of sediment was removed for grain size analyses, then the remainder of the grab sample was sieved through 0.5-mm sieve for infaunal analyses. The infaunal sample was placed in a container and preserved in 10% formalin with rose bengal stain.

6.2.2.7 Epifauna and Demersal Fishes

A 7.6-m mongoose trawl was towed for 10 min (bottom time) along the pre-plotted transects. The tow path of each trawl tow was logged into the Hypack navigation system. Once the trawl was on deck, the contents of the catch bag were sorted, then identified to the lowest practical taxon. All organisms were identified and returned to the sea. Identifications were recorded on standard trawl data sheets.

6.2.3 Laboratory Methods

6.2.3.1 Sediment Grain Size

Sediment grain size analyses were conducted using combined sieve and hydrometer analyses according to recommended American Society for Testing Materials (ASTM) procedures. Grain size samples were washed in demineralized water, dried, and weighed. Coarse and fine fractions (sand/silt) were separated by sieving through a U.S. Standard Sieve

Mesh No. 230 (62.5 µm). Sediment texture of the coarse fraction was determined at half-phi intervals by passing the sediment through nested sieves. The weight of the materials collected in each particle size class was recorded. Boyocouse hydrometer analyses were used to analyze the fine fraction (<62.5 µm).

6.2.3.2 Sediment Profiling Camera

After the color slides were developed, the images were scanned and stored in Kodak Photo-CD format. All digital images were analyzed using image analysis software. Calibration information was determined by measuring 1-cm graduations from the Kodak Color Separation Guide. This calibration information was applied to all images analyzed. Linear and area measurements were recorded as number of pixels and converted to scientific units using the calibration information. Measured parameters were recorded on an electronic spreadsheet. A quality assurance/quality control person checked all data prior to the final interpretation.

Parameters measured from sediment profiling camera images collected included the following:

- Sediment type (grain size major mode and range);
- Camera prism penetration depth;
- Small-scale surface boundary roughness;
- Thickness of depositional layers;
- Mud clasts (presence and diameter);
- Apparent redox potential discontinuity (RPD) depth;
- Infaunal successional stage; and
- Organism-Sediment Index (OSI).

A detailed explanation of how these measurements were performed and their interpretation is provided below.

Sediment Type

Sediment grain size major mode and range were visually estimated from the photographs by overlaying a grain size comparator that was at the same scale. This comparator was prepared by photographing a series of Udden-Wentworth size classes (equal to or less than coarse silt up to granule and larger sizes) with the sediment profiling camera. Seven grain size classes were on this comparator: 4 phi, 4 to 3 phi, 3 to 2 phi, 2 to 1 phi, 1 to 0 phi, 0 to -1 phi, and < -1 phi. The lower limit of optical resolution of the photographic system was about 62 µm, allowing recognition of grain sizes equal to or greater than coarse silt ($\geq$ 4 phi). The accuracy of this method has been documented by comparing SPI estimates with grain size statistics determined from laboratory sieve analyses.

The comparison of the images with Udden-Wentworth sediment standards photographed through the SPI optical system also was used to map near-surface stratigraphy such as sand-over-mud and mud-over-sand. When mapped on a local scale near facies boundaries, this stratigraphy can provide information on transport directions.

Camera Prism Penetration Depth

The sediment profiling camera prism penetration depth was measured from the bottom of the image to the sediment-water interface. Average penetration depth was determined by measuring across the entire cross-sectional image. Linear maximum and minimum depths of penetration also were measured. Maximum, minimum, and average penetration depths were recorded in the data file.

Prism penetration is potentially a noteworthy parameter; because the number of weights used in the camera was held constant throughout this survey, the camera functioned as a static-load penetrometer. Comparative penetration values from stations with similar grain size give an indication of the relative water content of the sediment. Highly bioturbated sediments and rapidly accumulating sediments tend to have the highest water contents and greatest prism penetration depths.

The depth of the camera's penetration into the bottom also reflects the bearing capacity and shear strength of local sediments. Over-consolidated or relic sediments and shell-bearing sands resist camera penetration. Highly bioturbated, sulfitic, or methanogenic muds are the least consolidated, and deep penetration is typical. Seasonal changes in camera prism penetration are typically observed at the same station and are related to the control of sediment geotechnical properties by bioturbation (Rhoads and Boyer, 1982). The effect of water temperature on bioturbation rates appears to be important in controlling both biogenic surface relief and prism penetration depth (Rhoads and Germano, 1982).

Small-Scale Surface Boundary Roughness

Surface boundary roughness was determined by measuring the vertical distance (parallel to the film border) between the highest and lowest points of the sediment-water interface. Surface boundary roughness (sediment surface relief) measured over a horizontal distance of 15 cm typically ranges from 0.02 to 3.8 cm and may be related to either physical structures (ripples, rip-up structures, mud clasts) or biogenic features (burrow openings, fecal mounds, foraging depressions). Biogenic roughness typically changes seasonally and is related to the interaction of bottom turbulence and bioturbational activities.

The camera must be level to take accurate boundary roughness measurements. In sandy sediments, boundary roughness can be a measure of sand wave height. On silt-clay bottoms, boundary roughness values often reflect biogenic features such as fecal mounds or surface burrows.

Thickness of Depositional Layers

Because of the camera's unique design, SPI can be used to detect the thickness of depositional and dredged material layers. SPI is effective in measuring layers ranging in thickness from 20 cm (the height of the SPI optical window) to 1 mm. During image analyses, the thickness of newly deposited sedimentary layers can be determined by measuring the linear distance between the pre- and post-disposal sediment-water interface. Recently deposited material usually is evident because of its unique optical reflectance and/or color relative to the underlying material representing the pre-disposal surface. Also, in most cases, the point of contact between the two layers and a textural change in sediment composition in the new layer are clearly visible, facilitating measurement of the thickness of the newly deposited layer.

Mud Clasts

When fine-grained, cohesive sediments are disturbed, either by physical bottom scour or faunal activity (e.g., decapod foraging), intact clumps of sediment often are scattered about the seafloor. These mud clasts can be seen at the sediment-water interface in the images. During analyses, the numbers of clasts were counted, the diameters of typical clasts were measured, and their oxidation states were assessed. The abundance, distribution, oxidation state, and angularity of mud clasts can be used to make inferences about the recent pattern of seafloor disturbance in an area.

Depending on their place of origin and the depth of disturbance of the sediment column, mud clasts can be reduced or oxidized (in the images, the oxidation state is apparent from the reflectance value; see the following subsection titled Apparent Redox Potential Discontinuity Depth). Also, once at the sediment-water interface, these mud clasts are subject to bottom-water oxygen levels and currents. Based on laboratory microcosm observations of reduced sediments placed within an aerobic environment, oxidation of reduced surface layers by diffusion alone is quite rapid, occurring within 6 to 12 hours (Germano, 1983). Consequently, the detection of reduced mud clasts in an obviously aerobic setting suggests a recent origin. The size and shape of the mud clasts also are revealing. Mud clasts may be moved and broken by bottom currents and animals (macro- or meiofauna; Germano, 1983). Over time, large angular clasts become small and rounded.

Apparent Redox Potential Discontinuity Depth

Aerobic near-surface marine sediments typically have higher reflectance values relative to underlying hypoxic or anoxic sediments. Surface sands washed free of mud also have higher optical reflectance than underlying muddy sands. These differences in optical reflectance are readily apparent in the images; oxidized surface sediment contains particles coated with ferric hydroxide (an olive or tan color when associated with particles), while reduced and muddy sediments below this oxygenated layer are darker, generally gray to black. The boundary between the colored ferric hydroxide surface sediment and underlying gray to black sediment is called the apparent RPD.

The depth of the apparent RPD in the sediment column is an important time-integrator of dissolved oxygen conditions within sediment porewaters. In the absence of bioturbating organisms, this high reflectance layer (in muds) typically will reach a thickness of 2 mm (Rhoads, 1974). This depth is related to the supply rate of molecular oxygen by diffusion into the bottom and the consumption of that oxygen by the sediment and associated microbiota. In sediments that have very high sediment oxygen demand (SOD), the sediment may lack a high reflectance layer even when the overlying water column is aerobic.

In the presence of bioturbating macrofauna, the thickness of the high reflectance layer may be several centimeters. The relationship between the thickness of this high reflectance layer and the presence or absence of free molecular oxygen in the associated porewaters must be assumed with caution. The actual RPD is the boundary (or horizon) that separates the positive Eh region of the sediment column from the underlying negative Eh region. The exact location of this Eh = 0 potential can be determined accurately only with microelectrodes; hence, the relationship between the change in optical reflectance, as imaged with the sediment profiling camera, and the actual RPD can be determined only by making the appropriate *in situ* Eh measurements. For this reason, the optical reflectance boundary, as imaged, was described in this study as the “apparent” RPD and it was recorded as a mean value. In general, the depth of the actual Eh = 0 horizon will be either equal to or slightly shallower than the depth of the optical reflectance boundary. This is because bioturbating organisms can mix ferric hydroxide-coated particles downward into the bottom below the Eh = 0 horizon. As a result, the apparent mean RPD depth can be used as an estimate of the depth of porewater exchange, usually through porewater irrigation (bioturbation). Biogenic particle mixing depths can be estimated by measuring the maximum and minimum depths of imaged feeding voids in the sediment column. This parameter represents the particle mixing depths of head-down feeders (mainly polychaetes).

The rate of depression of the apparent RPD within the sediment is relatively slow in organic-rich muds (on the order of 200 to 300 µm per day); therefore this parameter has a long time constant (Germano and Rhoads, 1984). The rebound in the apparent RPD also is slow (Germano, 1983). Measurable changes in the apparent RPD depth using the SPI optical technique can be detected over periods of 1 or 2 months. This parameter is used effectively to document changes (or gradients) that develop over a seasonal or yearly cycle related to water temperature effects on bioturbation rates, seasonal hypoxia, SOD, and infaunal recruitment. In sediment profile surveys of ocean disposal sites sampled seasonally or yearly throughout New England (performed under the Disposal Area Monitoring System Program for the USACE, New England Division), frequent monitoring with SPI technology repeatedly has documented a drastic reduction in apparent RPD depths at disposal sites immediately after dredged material disposal. This reduction was followed by a progressive post-disposal deepening of the apparent RPD (barring further physical disturbance). Consequently, time series RPD measurements can be a critical diagnostic element in monitoring the degree of recolonization in an area by the ambient benthos.

Apparent mean RPD depth also can be affected by local erosion. Peaks of disposal mounds commonly are scoured by divergent flow over mounds. This scouring can wash away fines and shell or gravel lag deposits, and can result in a very thin apparent RPD depth. During storm periods, erosion may completely remove any evidence of the apparent RPD (Fredette et al., 1988).

Another important characteristic of the apparent RPD is the contrast in reflectance values at this boundary. This contrast is related to the interactions among the degree of organic loading, the bioturbational activity in the sediment, and the levels of bottom-water dissolved oxygen in an area. High inputs of labile organic material increase SOD and, subsequently, sulfate reduction rates (and the abundance of sulfide end products). This results in more highly reduced (lower-reflectance) sediments at depth and higher RPD contrasts. In a region of generally low RPD contrasts, images with high RPD contrasts indicate localized sites of relatively high past inputs of organic-rich material such as organic or phytoplankton detritus, dredged material, and sewage sludge.

Infaunal Successional Stage

Information concerning infaunal successional stages in fine-grained sediments may be collected with SPI technology. These stages are recognized in the images by the presence of dense assemblages of near-surface polychaetes and/or subsurface feeding voids; both may be present in the same image. The concept of successional stages is based on the theory that organism-sediment interactions follow a predictable sequence after a major seafloor perturbation. This theory states that primary succession results in “the predictable appearance of macrobenthic invertebrates belonging to specific functional types following a benthic disturbance. These invertebrates interact with sediment in specific ways. Because functional types are the biological units of interest … our definition does not demand a sequential appearance of particular invertebrate species or genera” (Rhoads and Boyer, 1982). This theory is formally developed in Rhoads and Germano (1982) and Rhoads and Boyer (1982).

This continuum of change in animal communities after a disturbance (primary succession) has been divided arbitrarily into three stages: Stage I is the initial community of tiny, densely populated polychaete assemblages; Stage II is the start of the transition to head-down deposit feeders; and Stage III is the mature community of deep-dwelling, head-down deposit feeders.

After an area of bottom is disturbed (whether from natural or anthropogenic events), the first invertebrate assemblage (Stage I) appears within days after the disturbance. Stage I consists of dense assemblages of tiny tube-dwelling marine polychaetes that reach population densities of 10^4 to 10^6 individuals per m^2. These animals feed at or near the sediment-water interface and physically stabilize or bind the sediment surface by producing a mucous "glue" that they use to build their tubes. Sometimes deposited dredged material layers contain Stage I tubes still attached to mud clasts from their location of origin; these transported individuals are considered as part of the *in situ* fauna in the assignment of successional stages.

If there are no repeated disturbances to the newly colonized area, then these initial tube-dwelling suspension or surface-deposit feeding taxa are followed by burrowing, head-down deposit-feeders that rework the sediment deeper over time and mix oxygen from the overlying water into the sediment. Animals in these later-appearing communities (Stage II or III) are larger, have lower overall population densities (10 to 10^2 individuals per m^2), and can rework sediments to depths of 3 to 20 cm or more. These animals "loosen" the sedimentary fabric, increase the water content in the sediment (thereby lowering the sediment shear strength), and actively recycle nutrients because of the high exchange rate with the overlying waters resulting from their burrowing and feeding activities.

Organism-Sediment Index

The OSI is a summary statistic that is calculated on the basis of four independently measured SPI parameters: apparent mean RPD depth, infaunal successional stage, presence of methane gas, and low/no dissolved oxygen at the sediment-water interface. Table 6-2 shows how these parameters are summed to derive the OSI.

Table 6-2. Calculation of the Organism-Sediment Index based on sediment profile image parameters.

Parameter	Index Value
A. Apparent Mean RPD Depth (choose one)	
0.00 cm	0
>0 to 0.75 cm	1
0.76 to 1.50 cm	2
1.51 to 2.25 cm	3
2.26 to 3.00 cm	4
3.01 to 3.75 cm	5
>3.75 cm	6
B. Infaunal Successional Stage (choose one)	
Azoic	-4
Stage I	1
Stage I → II	2
Stage II	3
Stage II → III	4
Stage III	5
Stage I on III	5
Stage II on III	5
C. Chemical Parameters (choose one or both if appropriate)	
Methane present	-2
Low/no dissolved oxygen[a]	-4
Organism-Sediment Index = Total of above subset indices (A+B+C)	
Range: -10 to +11	

[a] This parameter is not based on a Winkler or polarigraphic electrode measurement, but on the imaged evidence of reduced, low reflectance (i.e., high-oxygen-demand) sediment at the sediment-water interface.

The highest possible OSI value is +11, which reflects a mature benthic community in relatively undisturbed conditions (generally a good yardstick for high benthic habitat quality). These conditions are characterized by deeply oxidized sediment, with a low inventory of anaerobic metabolites and low SOD, and by the presence of a Stage III community. OSI values of 6 or less indicate that the benthic habitat has experienced physical disturbance, eutrophication, or excessive bioavailable contamination in the recent past. The lowest possible OSI value is -10, which indicates that the sediment has a high inventory of anaerobic metabolites, has a high oxygen demand, and is azoic.

6.2.3.3 Infauna

Formalin-preserved infaunal samples were rinsed on a U.S. Standard No. 30 (0.59-mm) sieve and transferred to 70% isopropanol. Before sorting, samples were passed through a series of sieves (0.3, 0.5, 0.6, 1, and 2 mm) to separate the organisms into size classes. Samples were sorted by hand under dissecting microscopes. All sediment in each sample was examined by a technician who removed all infauna observed. Organisms were identified to lowest practical taxon and counted. A minimum of 10% of all samples were resorted by different technicians as a quality control measure. Voucher specimens of each taxon were archived at the Barry A. Vittor & Associates, Inc. laboratory.

6.2.4 Data Analysis

6.2.4.1 Water Column

Temperature, salinity, dissolved oxygen, and depth values were entered into an electronic spreadsheet and tabulated. Depth profiles were plotted for temperature-salinity and temperature-dissolved oxygen.

6.2.4.2 Sediment Grain Size

A computer algorithm was used to determine size distribution and provide interpolated size information for the fine fraction at 0.25-phi intervals. Percentages of gravel, sand, silt, and clay were calculated and recorded along with a Folk's description for each sample.

6.2.4.3 Sediment Profiling Camera

See Section 6.2.3.2 Laboratory Methods.

6.2.4.4 Infauna

Summary statistics including number of taxa, number of individuals, density, diversity (H'), evenness (J'), and species richness (*D*) were calculated for each sampling station. Diversity (H'), also known as Shannon′s Index (Pielou, 1966), was calculated as follows:

$$H' = -\sum_{S}^{i=1} p_i \ln\left(p_i\right)$$

where S is the number of taxa in the sample, i is the ith taxa in the sample, and p_i is the number of individuals of the ith taxa divided by (N) the total number of individuals in the sample.

Evenness (J') was calculated with Pielou′s (1966) index of evenness:

$$J' = \frac{H'}{\ln(S)}$$

where H' is Shannon′s index as calculated above and S is the total number of taxa in a sample.

Species richness (D) was calculated by Margalef′s index:

$$D = \frac{(S - 1)}{\ln(N)}$$

where S is the total number of taxa in the sample, and N is the number of individuals in the sample.

Spatial and temporal patterns in infaunal assemblages were examined with cluster analysis. Cluster analyses were performed on similarity matrices constructed from raw data matrices consisting of taxa and samples (station – survey). Only species-level taxa, with the exception of two species complexes that can be only reliably identified to genus, were included in the analyses. Of these taxa, only those contributing at least 0.1% of the total abundance of species level taxa were included. Raw counts of each individual infaunal taxon in a sample (n) were transformed with the $\log_{10}(n+1)$ transformation prior to similarity analysis. Both normal (stations) and inverse (taxa) similarity matrices were generated using the Bray-Curtis index that was calculated using the following formula:

$$B_{jk} = \frac{2\sum_i \min(x_{ij}, x_{ik})}{\sum_i (x_{ij} + x_{ik})}$$

where B_{jk} (for normal analysis) is the similarity between samples j and k; x_{ij} and x_{ik} are the abundances of species i in samples j and k. B ranges from 0.0 when two samples have no species in common to 1.0 when the distribution of individuals among species is identical between samples. For inverse analysis, the B_{jk} is the similarity between species j and k; x_{ij} and x_{ik} are the abundances of species j and k in sample i.

Normal similarity matrices were clustered using the group averaging method of clustering, and inverse similarity matrices were clustered using the flexible sorting method of clustering (Boesch, 1973). Flexible sorting was performed with $\beta = -0.25$, a widely accepted value for this analysis (Boesch, 1973).

The extent to which sample groups formed by normal cluster analysis of the entire data set could be explained by environmental variables such as sediment grain size parameters was examined by canonical discriminant analysis (SAS Institute Inc., 1989). Canonical discriminant analysis identifies the degree of separation among predefined groups of variables in multivariate space. This analysis examined the relationships among the environmental variables and the station groups as indicated by the normal cluster analysis.

6.2.4.5 Epifauna and Demersal Fishes

Raw counts of individual epifaunal and demersal fish taxa were tabulated by sand resource area for both field surveys.

6.3 RESULTS

6.3.1 Water Column

Raw data for water column profiles made during Survey 1 are provided in Appendix C2, Table C2-1. Depth profiles of temperature-salinity and temperature-dissolved oxygen for the May 1998 Survey 1 are shown in Figures 6-6 and Figures 6-7. Temperature profiles showed similar patterns of gradual decrease from surface to bottom within all four areas. Surface temperatures varied little among areas and ranged from 19.4°C in Area 4 to 21.3°C in Areas 1 and 3. Bottom temperatures ranged from 13.1°C in Area 4 to 13.4°C in Area 1. Surface salinity generally increased rapidly to about 5 m then gradually increased to near-bottom waters, except in Area 3 where salinity decreased just below the surface then increased to near-bottom waters. Surface salinities ranged from 21.8 ppt in Area 2(out) to 28.3 in Area 4. Bottom salinities ranged from 32.6 ppt in Area 1 to 33.1 ppt in Area 4. Dissolved oxygen profiles generally decreased from surface to bottom. Surface dissolved oxygen values ranged from 8.22 mg/L in Area 4 to 8.61 mg/L in Area 2(out). Bottom dissolved oxygen values ranged from 7.36 mg/L in Area 3 to 7.88 mg/L in Area 4.

Raw data for water column profiles made during Survey 2 are given in Appendix C2, Table C2-2. Temperature, salinity, and dissolved oxygen profiles made during the September 1998 Survey 2 are shown in Figures 6-8 and 6-9 (the water column profile made outside of Area 2 [see Section 6.2.1] was not plotted, but the raw data are in Table C2-2). Water column temperature was generally uniform within all of the sand resource areas, decreasing much less from surface to bottom during the September survey as compared to the May survey. Surface temperatures ranged from 24.0°C in Areas 1 and 3 to 24.4°C in Area 2(in). Salinity profiles deviated little from vertical lines, unlike the May profiles. Surface salinity ranged from 26.1 ppt in Area 3 to 31.9 ppt in Area 2(in). Bottom salinities ranged from 27.0 ppt in Area 2(out) to 32.4 ppt in Area 4. Dissolved oxygen values decreased slightly from surface to bottom with the exception of Area 3. Surface dissolved oxygen values ranged from 6.74 mg/L in Area 1 to 7.18 mg/L in Area 2(out). Bottom dissolved oxygen values ranged from 3.71 mg/L in Area 3 to 5.95 mg/L in Area 2(out). In general, dissolved oxygen values for all areas were lower during the September survey than during the May survey.

6.3.2 Sediment Grain Size

Sediment grain size of Smith-McIntyre grab samples taken in the sand resource areas during the May 1998 Survey 1 consisted mostly of sand (Appendix C3, Table C3-1). Eighteen of the 20 samples were composed of greater than 92% sand. In Sand Resource Area 1, all but one sample contained greater than 92% sand; the remaining sample was composed of 77% sand and 22.5% gravel. Both samples collected in Area 2 contained greater than 92% sand. In Area 3, four of five samples contained greater than 92% sand; the remaining sample contained 75% sand and 24% gravel. All three samples from Area 4 contained greater than 97% sand. Single samples from each of the two adjacent stations contained 98% and 97% sand.

General patterns of grain size composition in the grab samples taken during the September 1998 Survey 2 were similar to the patterns seen during the May 1998 Survey 1 (Appendix C3, Table C3-2). Sand characterized most grab samples with 42 of 50 grab samples containing greater than 95% sand. In Sand Resource Area 1, 14 of 20 samples contained greater than 95% sand. The remaining six samples contained mostly sand; in five of these samples, gravel made up most of the non-sand proportions (ranging from 8% to 13%); in the other sample, silt (8%) and clay (30%) composed most of the non-sand fraction. This was

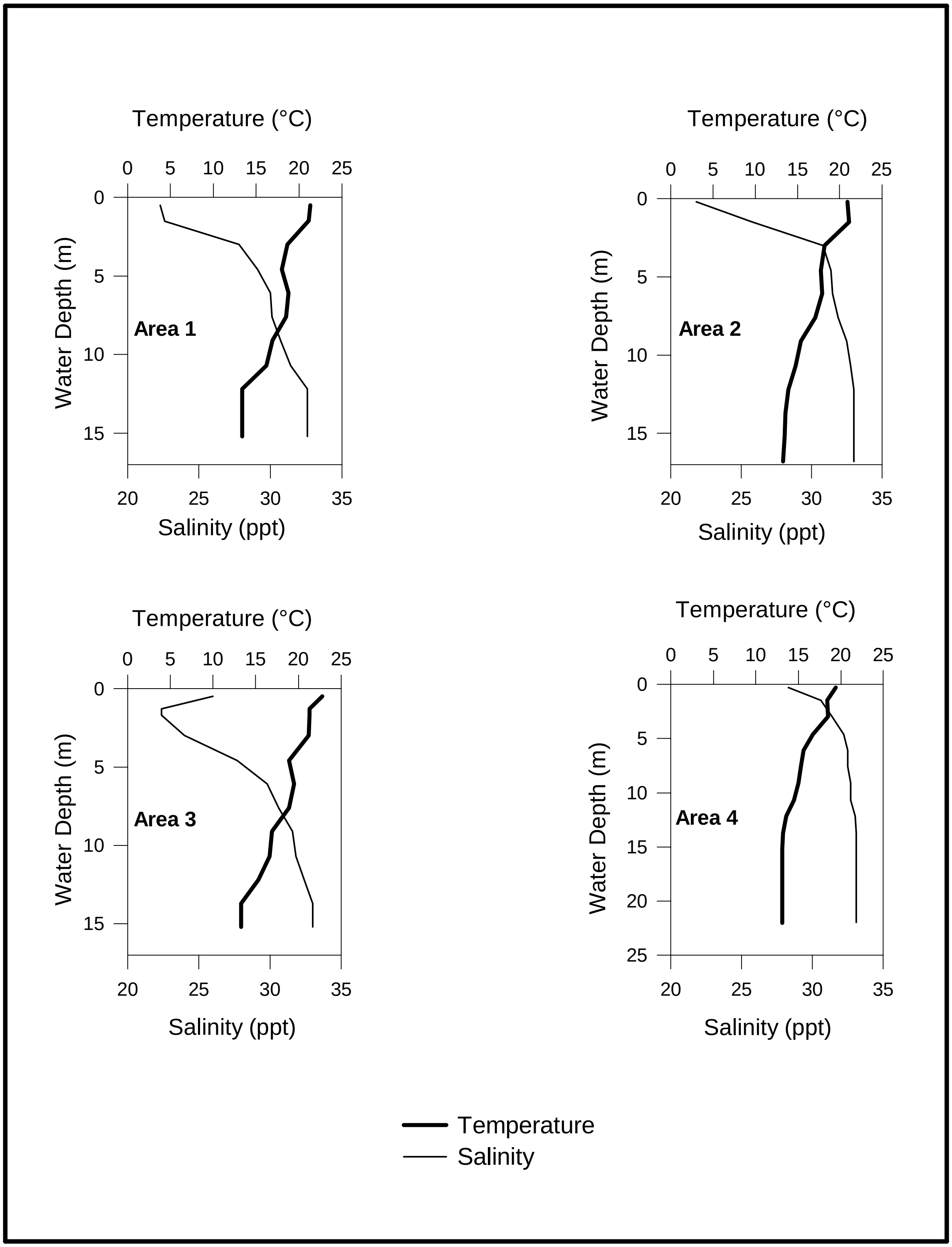

Figure 6-6. Temperature and salinity profiles recorded by Hydrolab during the May 1998 survey in the four sand resource areas offshore North Carolina.

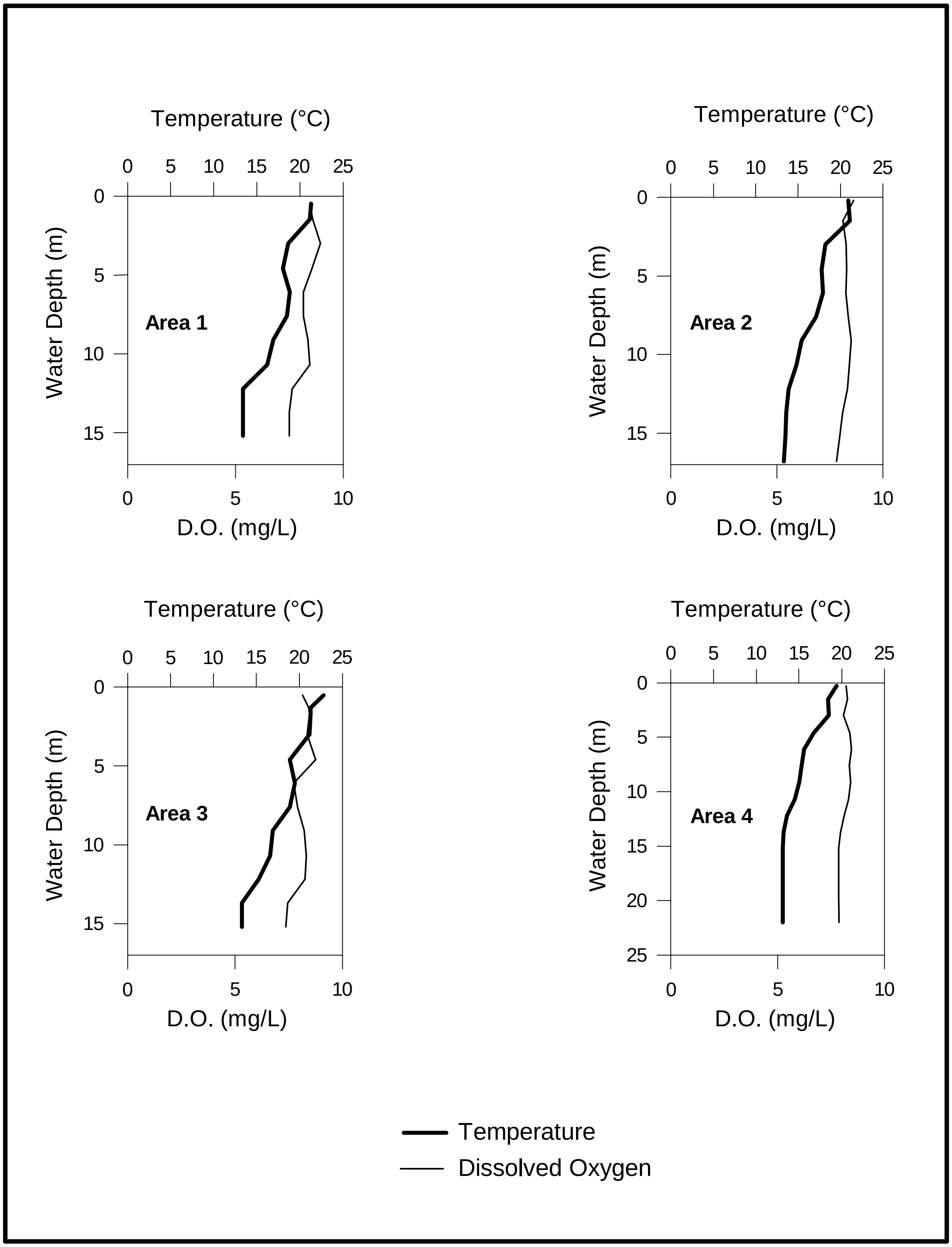

Figure 6-7. Temperature and dissolved oxygen profiles recorded by Hydrolab during the May 1998 survey in the four sand resource areas offshore North Carolina.

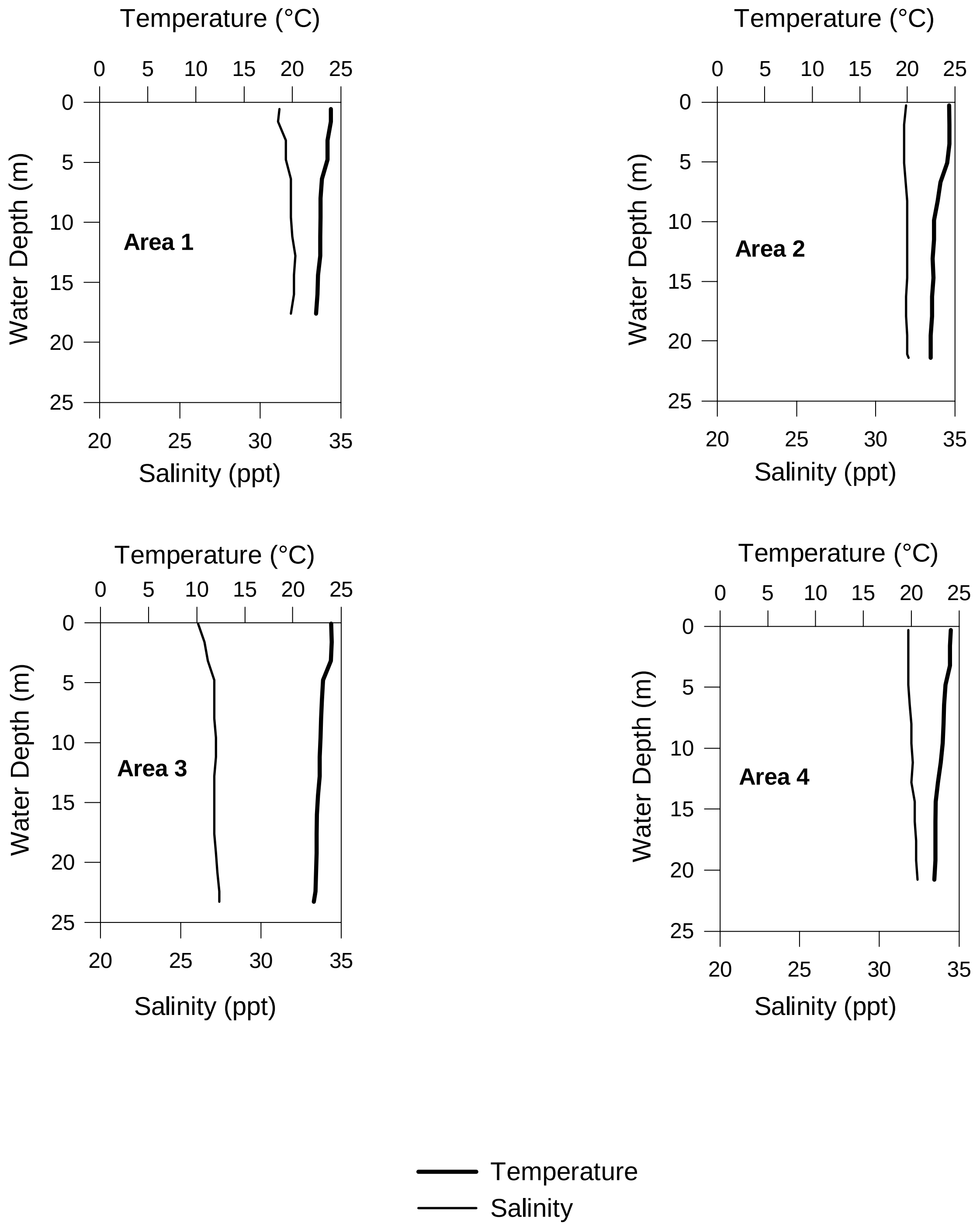

Figure 6-8. Temperature and salinity profiles recorded by Hydrolab during the September 1998 survey in the four sand resource areas offshore North Carolina.

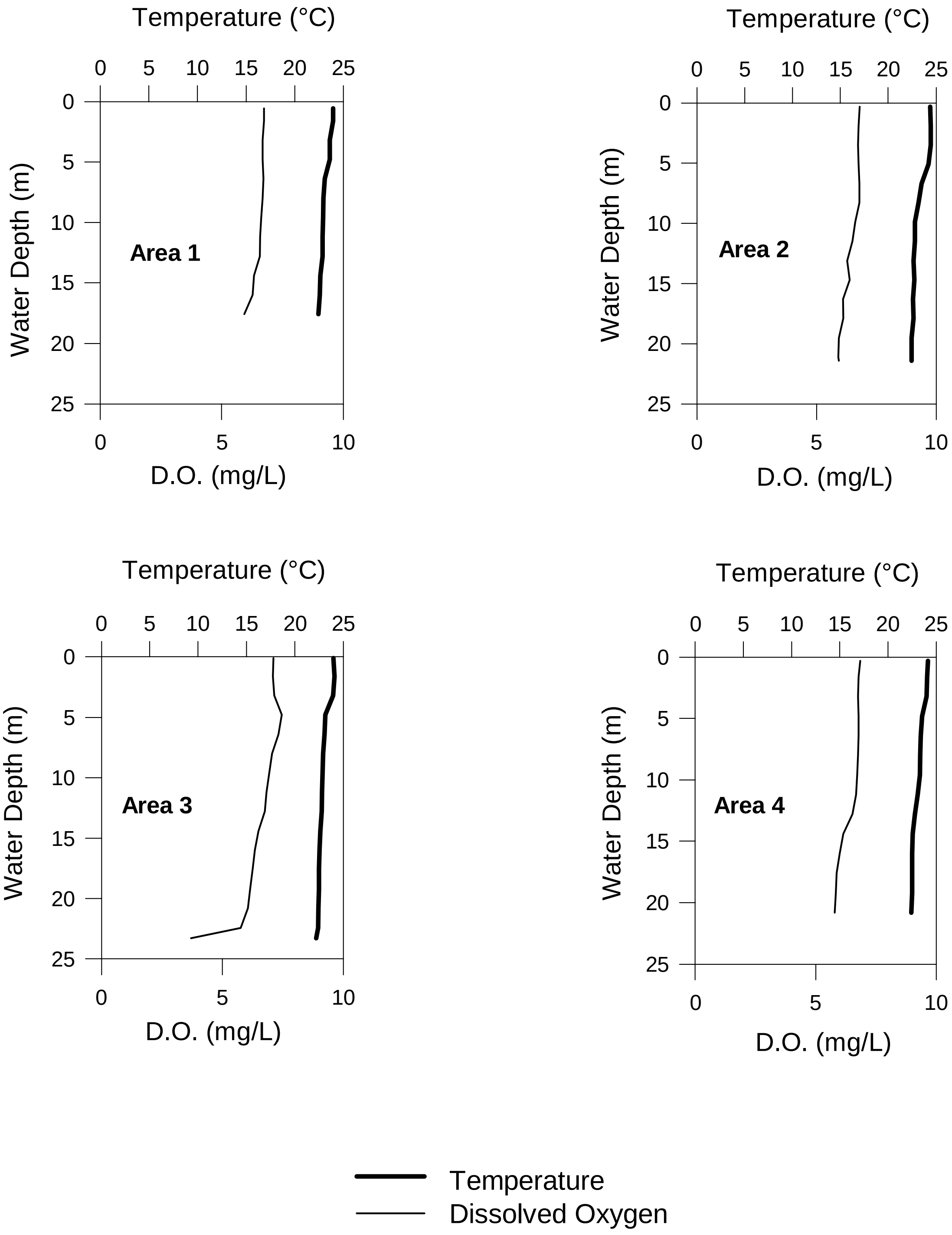

Figure 6-9. Temperature and dissolved oxygen profiles recorded during the September 1998 survey in the four sand resource areas offshore North Carolina.

the only sample collected during the September 1998 Survey 2 that contained appreciable proportions of silt and clay. All five samples collected in Area 2 contained greater than 99% sand. In Area 3, 11 of 13 samples contained greater than 98% sand; gravel composed 35% and 21% of the non-sand fractions of the two remaining samples. All 10 samples from Area 4 contained greater than 95% sand. The adjacent stations each contained 99% sand.

6.3.3 Sediment Profiling Camera

Sediment profiling camera images were collected during both field surveys. Data from the Survey 1 images are in Appendix C4, Table C4-1. Data from the Survey 2 images are in Appendix C4, Table C4-2.

6.3.3.1 Area 1

During May, 20 SPI stations were sampled in Area 1, in water depths ranging from 15 m (the shallowest station sampled in the survey) to 23 m, representing almost the total range of water depths sampled in the entire survey (Adjacent Station R1 in 24 m was the deepest station sampled in the May survey). Sediments throughout this area were fairly uniform, with stations showing a grain size major mode primarily of either very fine sand (4 to 3 phi) or fine sand (3 to 2 phi). Bedforms were evident in almost every image collected from this area, indicating a fairly high-energy bottom kinetic regime. Variation in sediment grain size major mode (Figure 6-10) did not correspond with water depth, but more likely represented whether the profile image was collected on the upcurrent or downcurrent flank of the bedform (Figure 6-11).

While a small number of images (8 out of 40) showed poorly-sorted sediments (Figure 6-12), most stations were represented by a total grain size range in the sand-sized fraction with sediments that were well-sorted (Figure 6-13). Evidence of bedload transport was apparent at Stations 17 and 20, where rippled, coarse-sediment surface layers showed distinct contact boundaries with underlying finer sands (Figure 6-14). Small-scale surface boundary roughness values ranged from 0.4 cm (Station 5) to 6.31 cm (Station 13; Figure 6-15); surface roughness elements were caused by the physical forces (bottom currents, wave energy) that created the sand ripples present at the sediment-water interface.

Sediment profiling camera prism penetration across the area ranged from a low of 2.2 cm in one of the replicate images from Station 9 to a maximum of 7.7 cm in one of the replicate images from Station 20 (Figure 6-16). Variation in prism penetration from station to station within the study area did not follow any distinct pattern, nor was it correlated with either sediment grain size major mode (Figure 6-10) or water depth.

Evidence of infaunal invertebrate activity was present at most of the stations in the form of either large, distinct burrows (Figure 6-17), large polychaete tubes projecting above the sediment-water interface (Figure 6-18), or more subtle subsurface burrow structures or faunal appendages (Figure 6-19). One quarter of the stations sampled (Stations 1, 6, 9, 16, and 20) had no clear evidence of substantial infaunal reworking activity, although the high sediment water content at Station 20 is most likely due to intense infaunal bioturbation. One of the images from Station 8 showed an intact surface layer of diatoms present (Figure 6-20) that would serve to stabilize the sediment surface and make it more resistant to erosion and transport. With the exception of the distinct tubicolous fauna at Stations 2 and 9 and the large burrows at Station 5, the remaining 12 stations that did show evidence of infaunal activity (subsurface burrow network) had sedimentary structures similar enough that one would infer infaunal community composition to be fairly uniform among these stations.

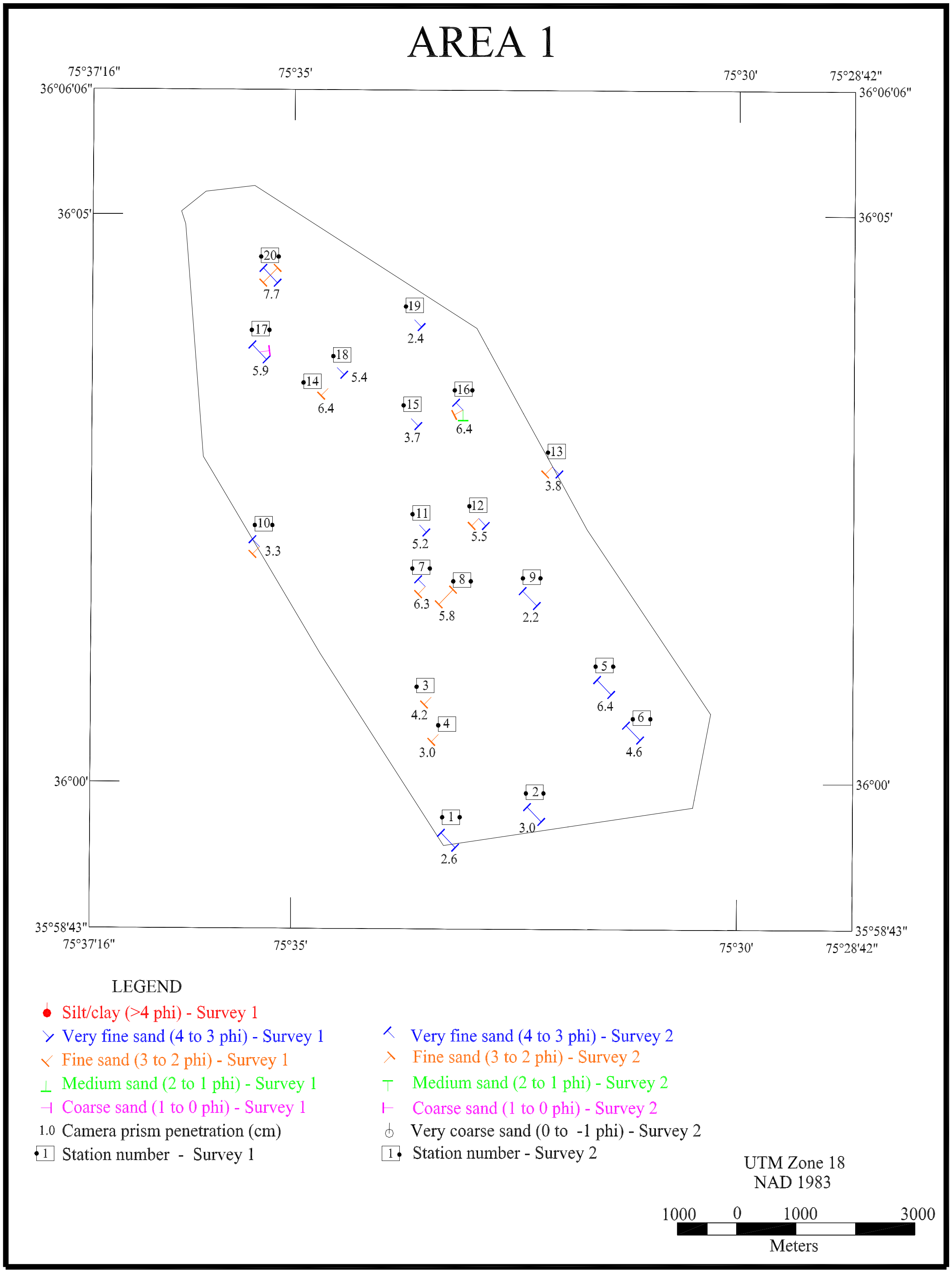

Figure 6-10. Spatial distribution of sediment grain size major mode (Surveys 1 and 2) and camera prism penetration depth (Survey 1) based on sediment profiling in North Carolina Sand Resource Area 1.

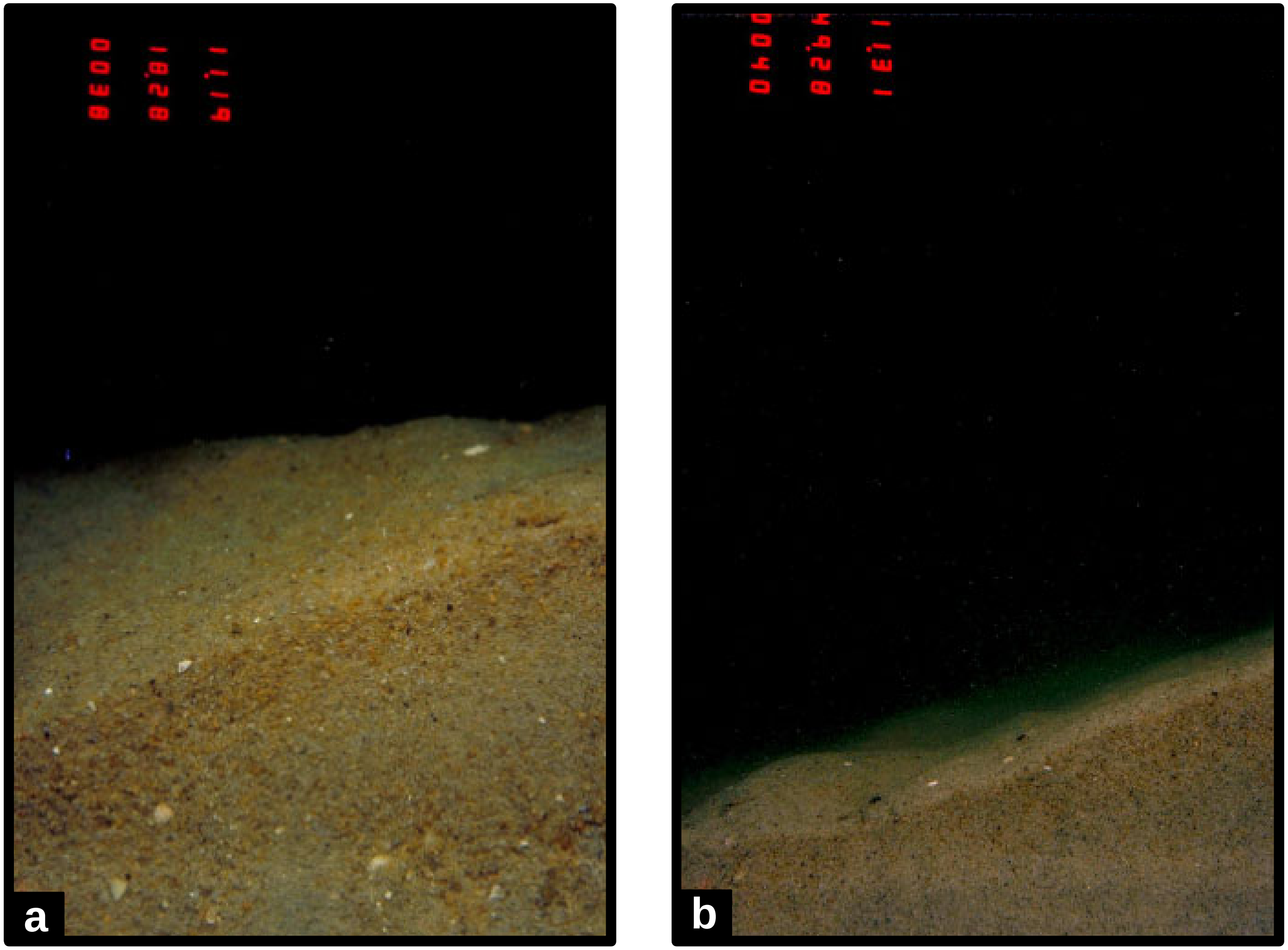

Figure 6-11. a. Sediment profile image from Station 14, Area 1, May 1998, Survey 1 showing the presence of bedforms and a grain size major mode of 3 to 2 phi (image width represents 15 cm). b. Sediment profile image from Station 15, Area 1, May 1998, Survey 1 showing the presence of bedforms and a grain size major mode of 4 to 3 phi (image width represents 15 cm).

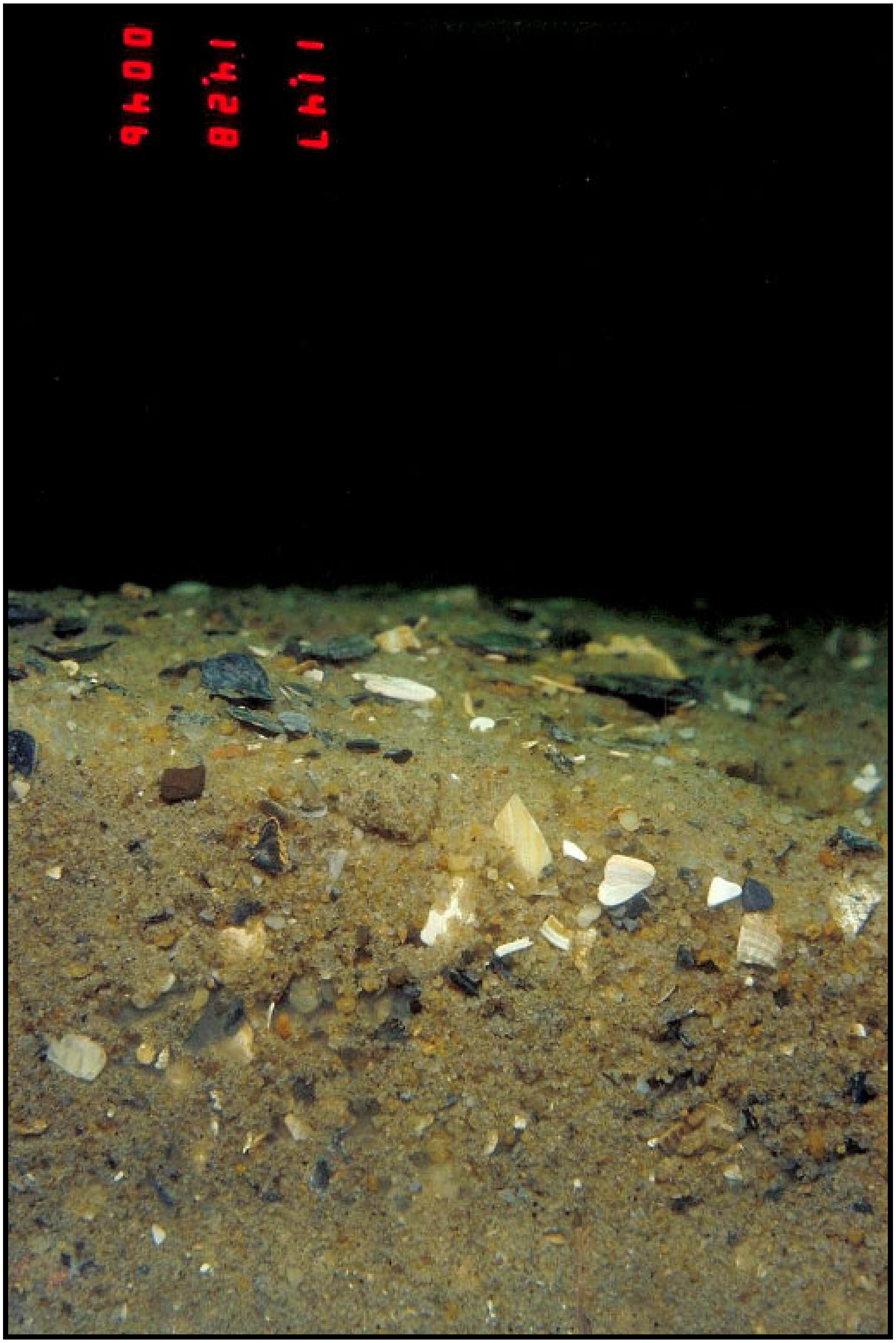

Figure 6-12. Sediment profile image from Station 16, Area 1, May 1998, Survey 1 showing poorly-sorted sediments with shell hash not only on the sediment surface but admixed down to a depth of 7 cm (image width represents 15 cm).

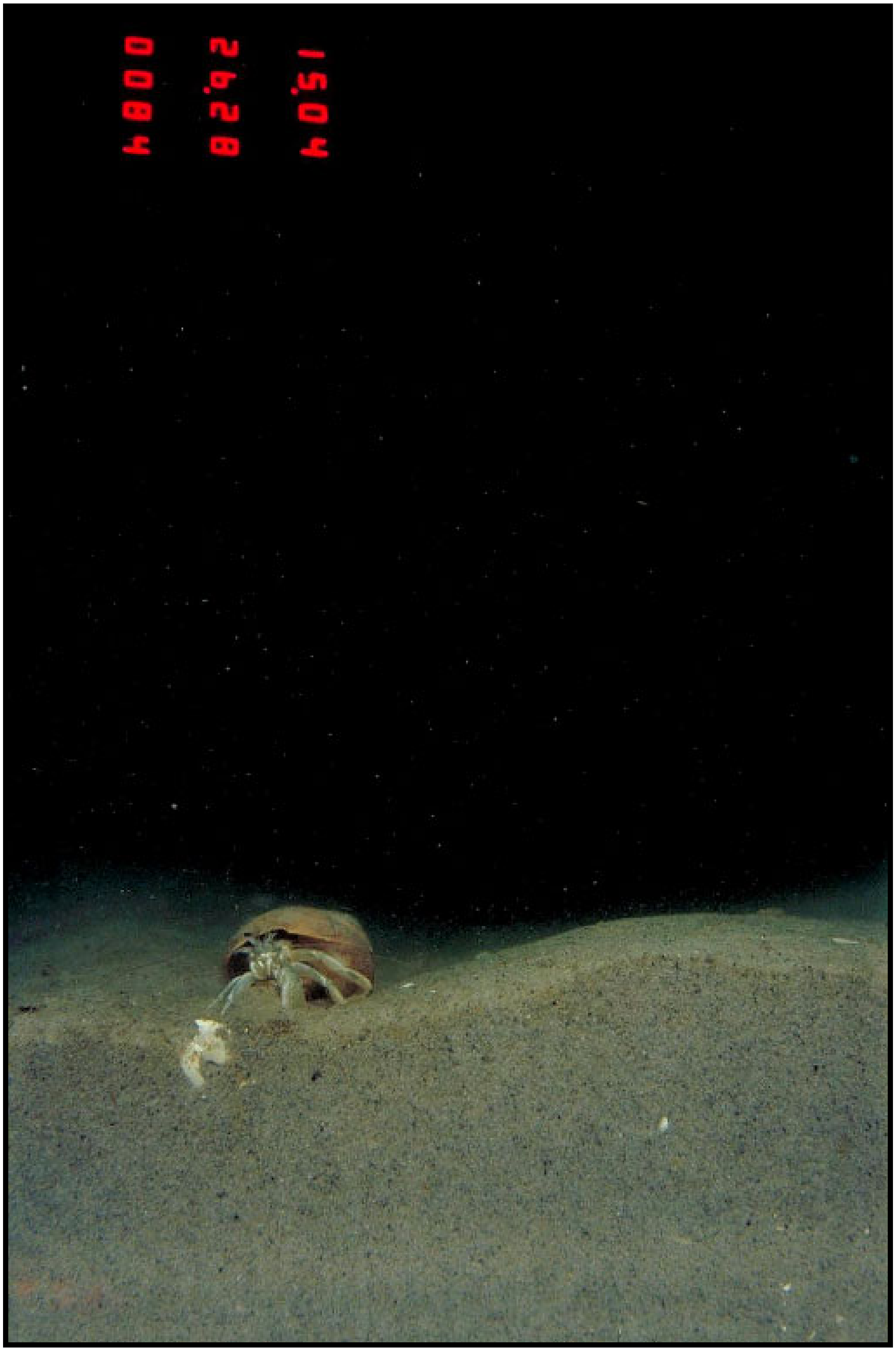

Figure 6-13. Sediment profile image from Station 6, Area 1, May 1998, Survey 1 showing well-sorted sediments in the very-fine-to-fine-sand range; note the hermit crab on the sediment surface (image width represents 15 cm).

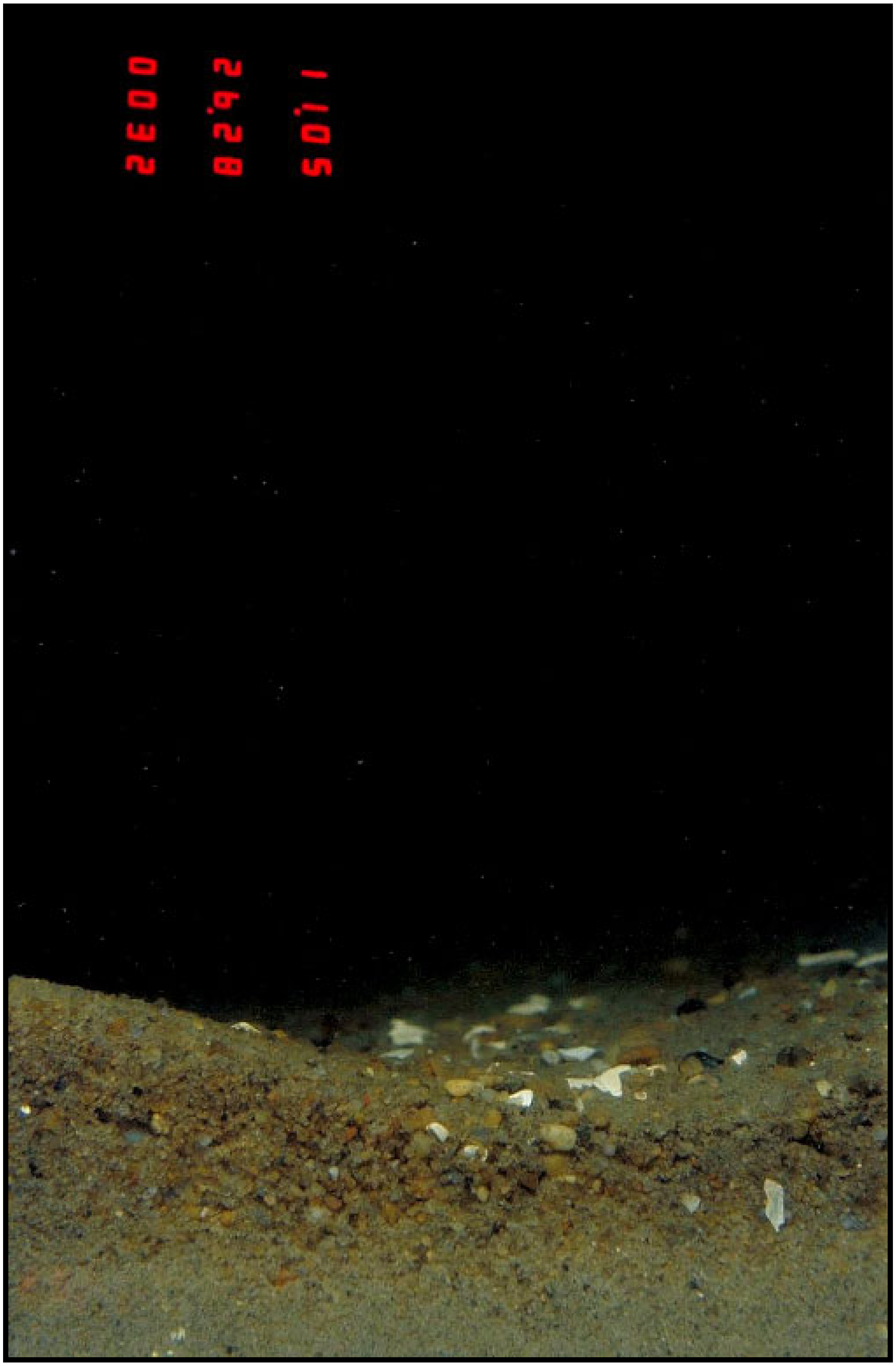

Figure 6-14. Sediment profile image from Station 17, Area 1, May 1998, Survey 1 showing a distinct demarcation between the coarse surface layer and underlying fine sands (image width represents 15 cm).

Figure 6-15. Sediment profile image from Station 13, Area 1, May 1998, Survey 1; boundary roughness values from all images in Area 1 were primarily due to surface relief from the physical forces that created the sand ripples present throughout the area (image width represents 15 cm).

Figure 6-16. Sediment profile image from Station 20, Area 1, May 1998, Survey 1; note that grain size is similar to that of other images, but prism penetration is greater, which is a function of lowered sediment shear strength (image width represents 15 cm).

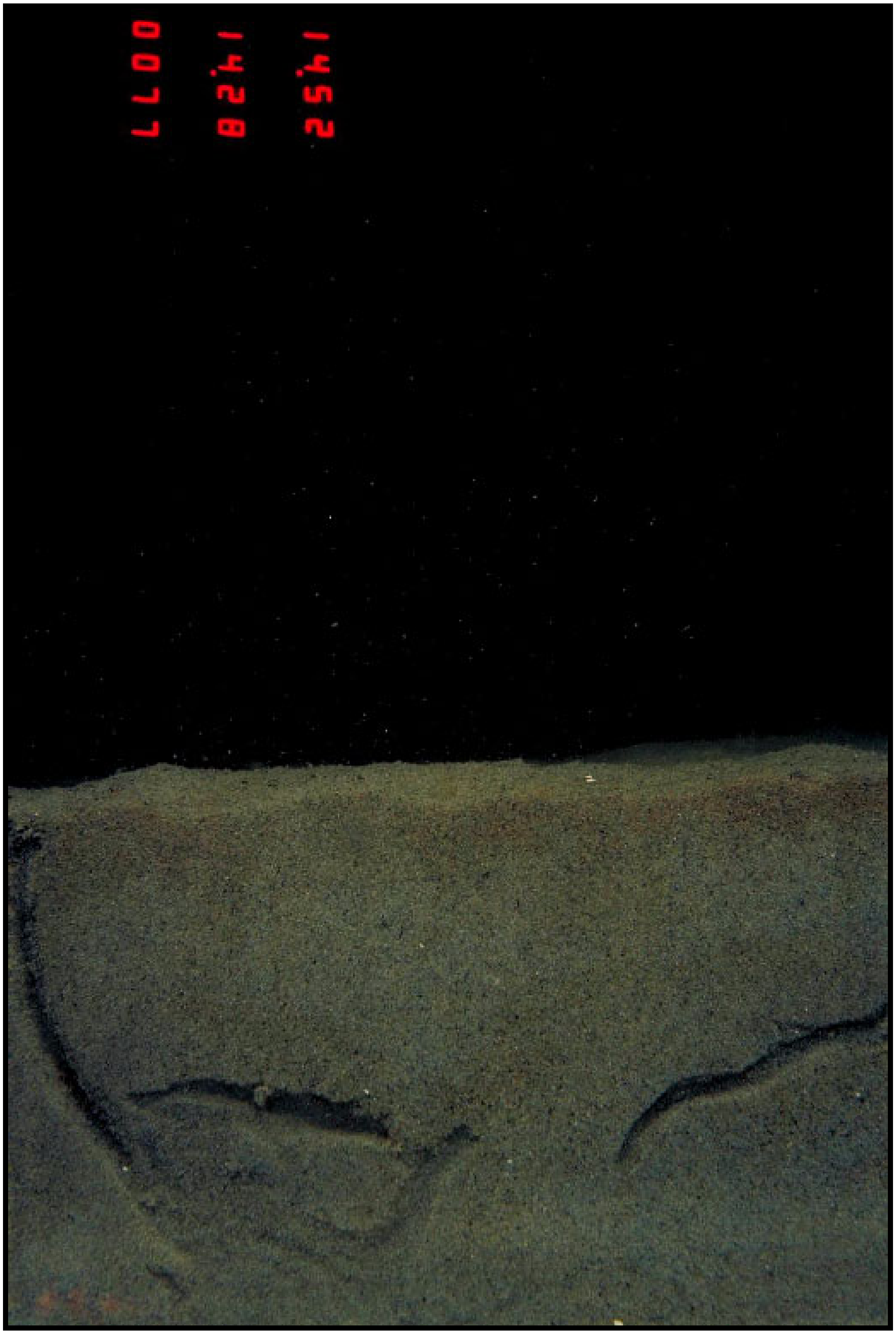

Figure 6-17. Sediment profile image from Station 5, Area 1, May 1998, Survey 1 showing an extensive network of subsurface burrow structures created by errant infauna (image width represents15 cm).

Figure 6-18. Sediment profile image from Station 2, Area 1, May 1998, Survey 1 showing tubicolous polychaetes projecting above the sediment-water interface (image width represents 15 cm).

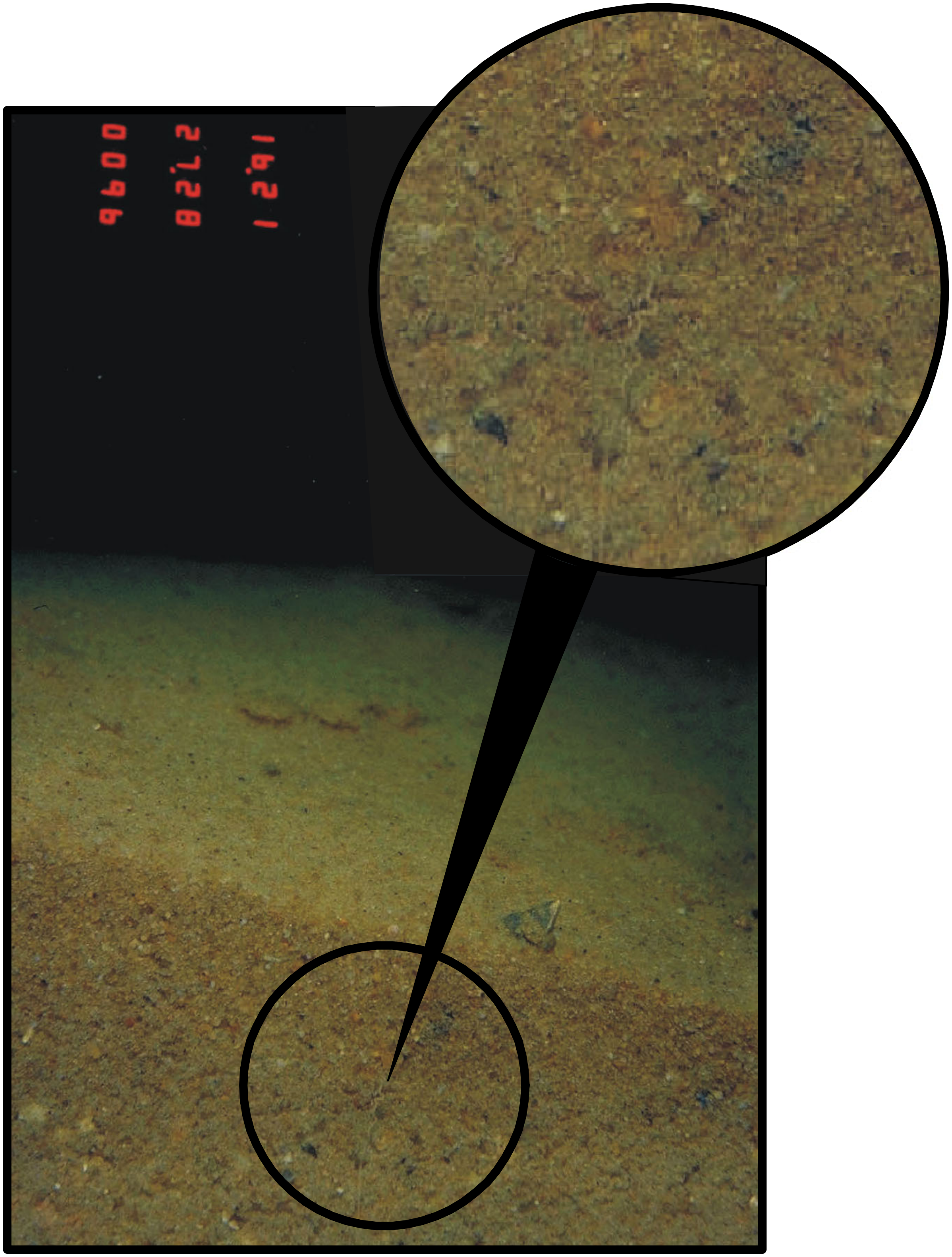

Figure 6-19. Sediment profile image from Station 3, Area 1, May 1998, Survey 1 with thin, white polychaete palp (arrow) being retracted back to the animal, which is below prism penetration depth (image width represents 15 cm).

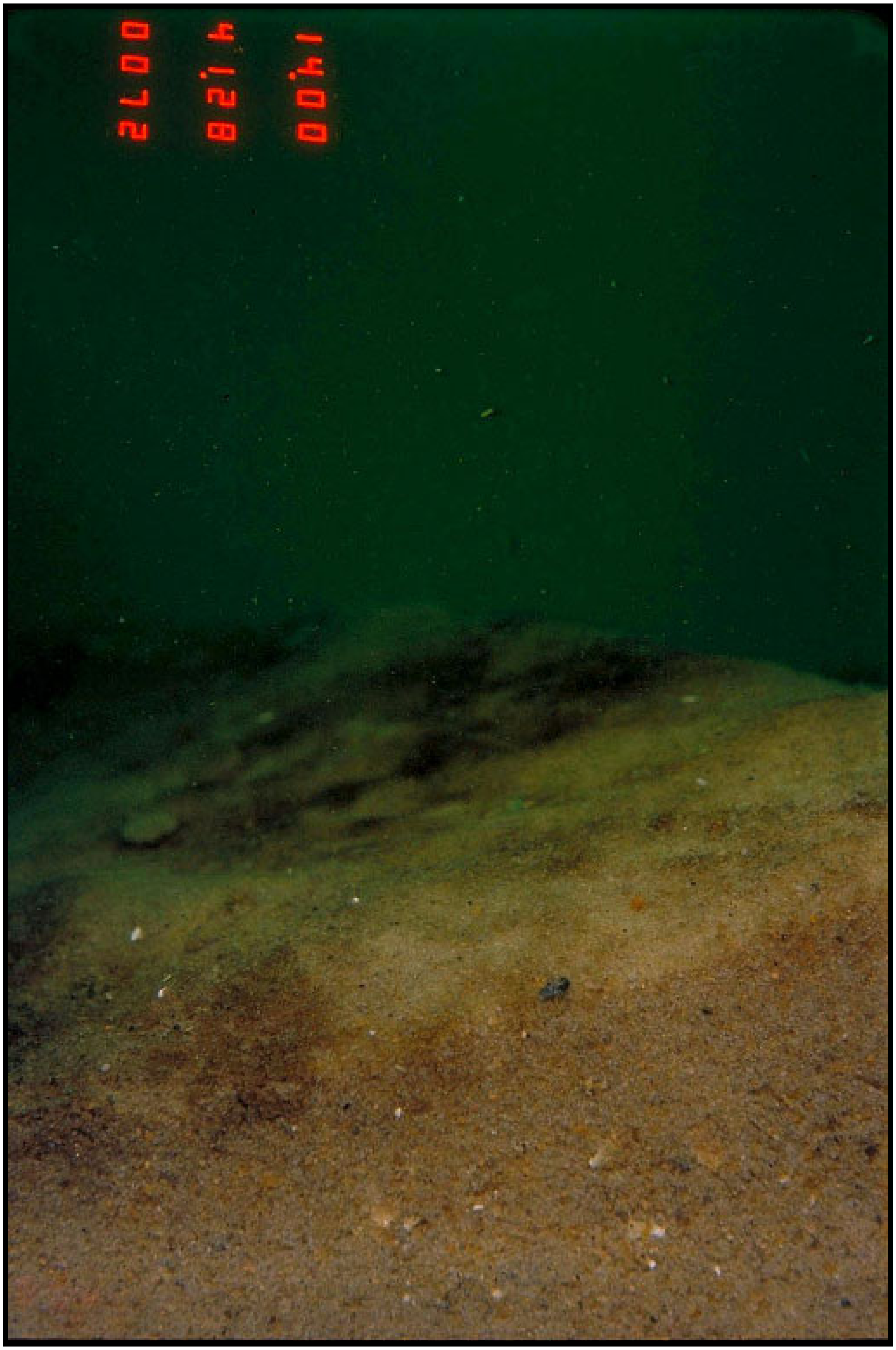

Figure 6-20. Sediment profile image from Station 8, Area 1, May 1998, Survey 1; the darker areas on the sediment surface are mats of benthic diatoms (image width represents 15 cm).

During the September survey, 11 SPI stations were sampled in Area 1 (Figure 6-10). Sediments were uniformly sandy with modal grain sizes of 4 to 3 phi in most images. Two images from Station 8 and one image from Station 20 had modal grain sizes of 3 to 2 phi. Boundary roughness ranged from 0.34 to 3.02 during this survey. Prism penetration ranged from 1.31 to 6.37 cm.

Most images collected from Area 1 during the September survey revealed some biotic activity, including infaunal burrows (Figure 6-21), surficial fecal casts, and megafaunal burrows. Of the 22 images examined from the area, only 3 images indicated infaunal successional stages: Stage I in one image from Station 5, and Stage III in one image from Station 1 and one image from Station 5.

6.3.3.2 Area 2

Area 2 was the smallest of the four areas surveyed. Only five SPI stations were sampled in Area 2 during the May 1998 survey from water depths ranging from 15 to 19 m. As in Area 1, sediments were well-sorted and very uniform throughout the area, with a grain size major mode ranging from fine sand (3 to 2 phi) in the northern half of the area to very fine sand (4 to 3 phi) in the southern half of the area (Figure 6-22). Bedforms also were evident at every location sampled (Figure 6-23). Sediment profiling camera prism penetration ranged from a low of 3.1 cm at Station 5 to a maximum of 6.0 at Station 2 (Figure 6-22); as in Area 1, penetration depth did not vary consistently either with grain size major mode or with water depth.

While organic concentrations in the sediments appeared to be rather low, judging from optical reflectance signatures, there was evidence of a thin layer (1 to 3 mm) deposit of organic material on the sediment surface at Station 4 (Figure 6-24). Structural evidence of faunal activity was different than in Area 1; the infaunal community in Area 2 appeared to consist of larger-sized individuals than those found in Area 1 as evidenced by the presence of large fecal casts on the sediment surface at three stations (Stations 2, 3, and 4; Figure 6-25).

The two SPI stations (Stations 2 and 4) sampled during the September survey (Figure 6-22) exhibited modal grain sizes of 3 to 2 phi and 4 to 3 phi, respectively. Prism penetration ranged from 3.1 to 6.0 cm.

There was evidence of infaunal activity noted among the images. One image (Figure 6-26) from Station 4 was assigned infaunal successional Stage III. A crab was present in one image (Figure 6-27), but epifauna was not prevalent in the images.

6.3.3.3 Area 3

Area 3 had the widest range of sediment types of the four areas sampled, based on 13 SPI stations surveyed during May 1998 in water depths ranging from 16 to 23 m. While most of these 13 stations had a sediment grain size major mode of very fine sand (4 to 3 phi), there was a line of stations (Stations 2, 4, 5, and 6) that varied dramatically in grain size, with grain size major mode shifting up or down from station to station (Figure 6-28). These abrupt shifts were not correlated with depth; for example, Stations 6 and 7 were in similar water depths (21.0 and 21.3 m, respectively), but sediment type differed dramatically (coarse sand and shell hash at Station 6, very fine sand at Station 7; Figure 6-29). Station 5 had unique sediment major mode and stratigraphy; it was the only station in this survey that had a thin surface layer (approximately 4 cm) of fine sand covering a silt-clay (>4 phi) substratum (Figure 6-30).

Camera prism penetration depth was similar to the other areas surveyed, ranging from a minimum of 2.2 cm to a maximum of 6.2 cm. The small variability in prism penetration did not correlate with sediment type or grain size major mode.

Figure 6-21. Sediment profile image from Station 2, Area 1, September 1998, Survey 2 showing surface roughness elements caused by infaunal burrowing activity; the crater-like rim of a large burrow opening can be seen in the left background of the image (image width represents 15 cm).

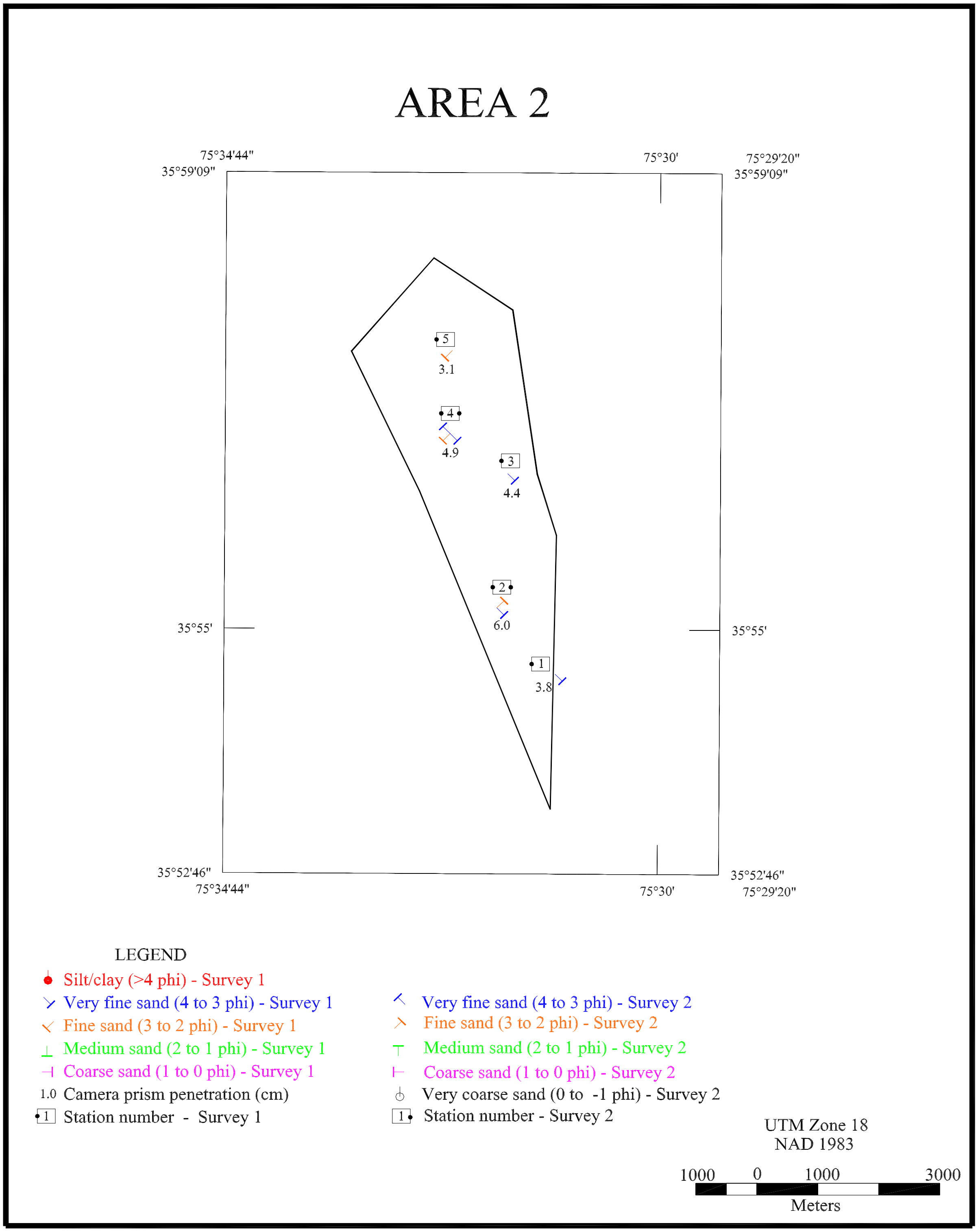

Figure 6-22. Spatial distribution of sediment grain size major mode (Surveys 1 and 2) and camera prism penetration depth (Survey 1) based on sediment profiling in North Carolina Sand Resource Area 2.

Figure 6-23. Sediment profile image from Station 1, Area 2, May 1998, Survey 1 showing the presence of bedforms and a grain size major mode of 4 to 3 phi (image width represents 15 cm).

Figure 6-24. Sediment profile image from Station 4, Area 2, May 1998, Survey 1 showing a thin surface deposit of fine-grained material with a grain size >4 phi (image width represents 15 cm).

Figure 6-25. Sediment profile image from Station 2, Area 2, May 1998, Survey 1; arrows point to fecal casts on the sediment surface from infaunal deposit feeders (image width represents 15 cm).

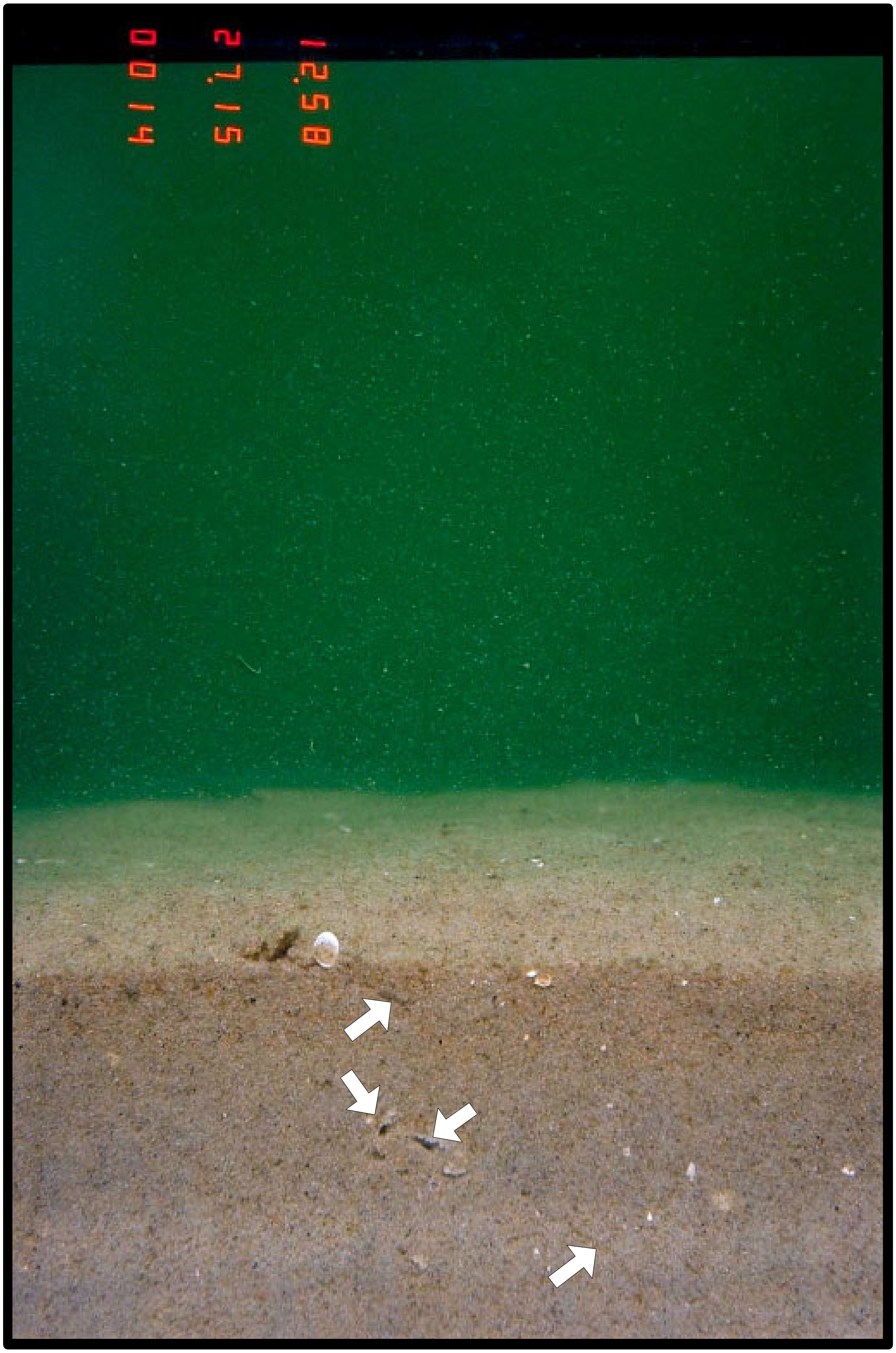

Figure 6-26. Sediment profile image from Station 4, Area 2, September 1998, Survey 2; arrows indicate traces of linear burrows and places where the camera prism has transected subsurface burrow structures (image width represents 15 cm).

Figure 6-27. Sediment profile image from Station 2, Area 2, September 1998, Survey 2 showing a crab's eyes peering just above the sediment surface at the camera lens (image width represents 15 cm).

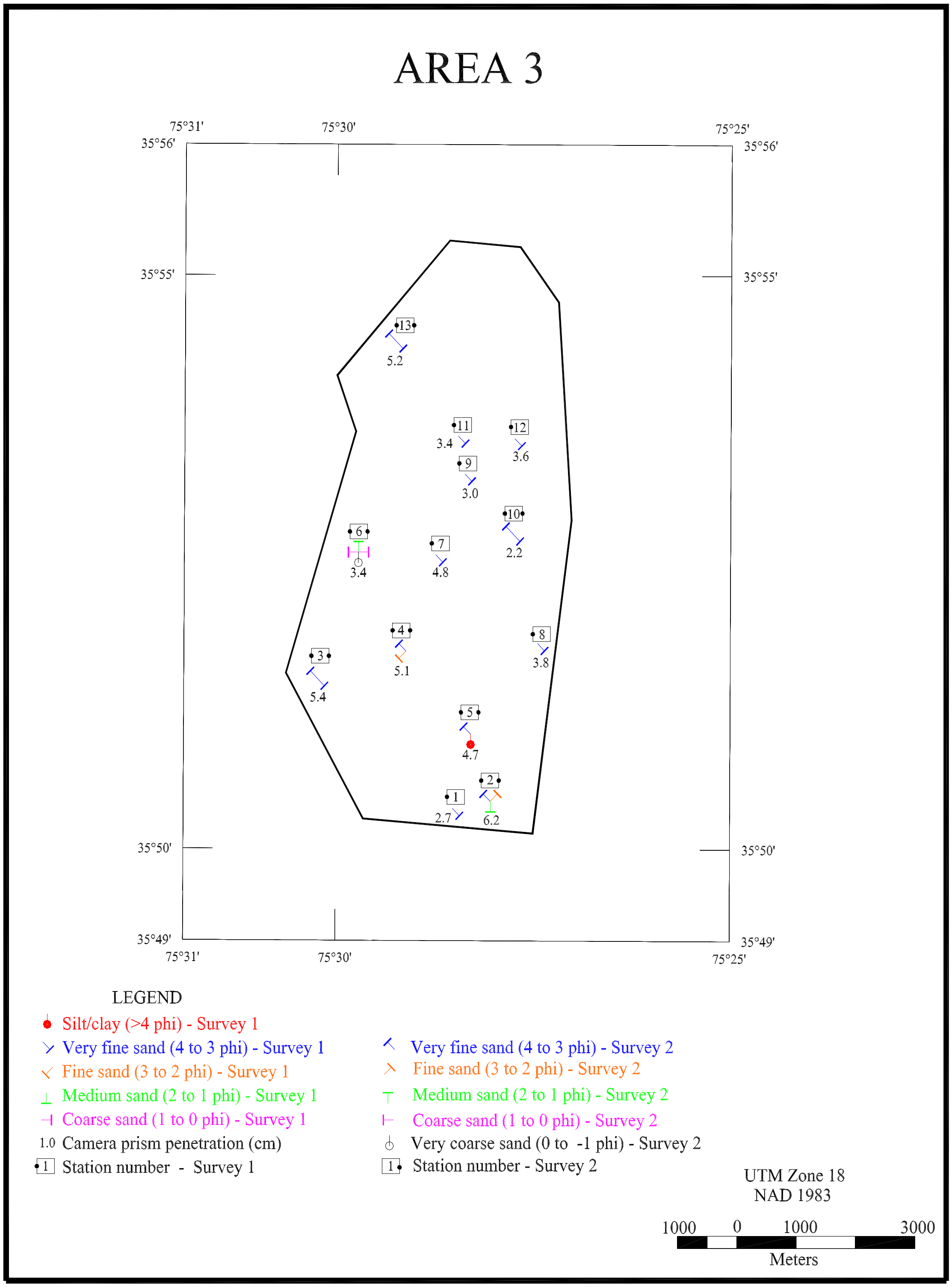

Figure 6-28. Spatial distribution of sediment grain size major mode (Surveys 1 and 2) and camera prism penetration depth (Survey 1) based on sediment profiling in North Carolina Sand Resource Area 3.

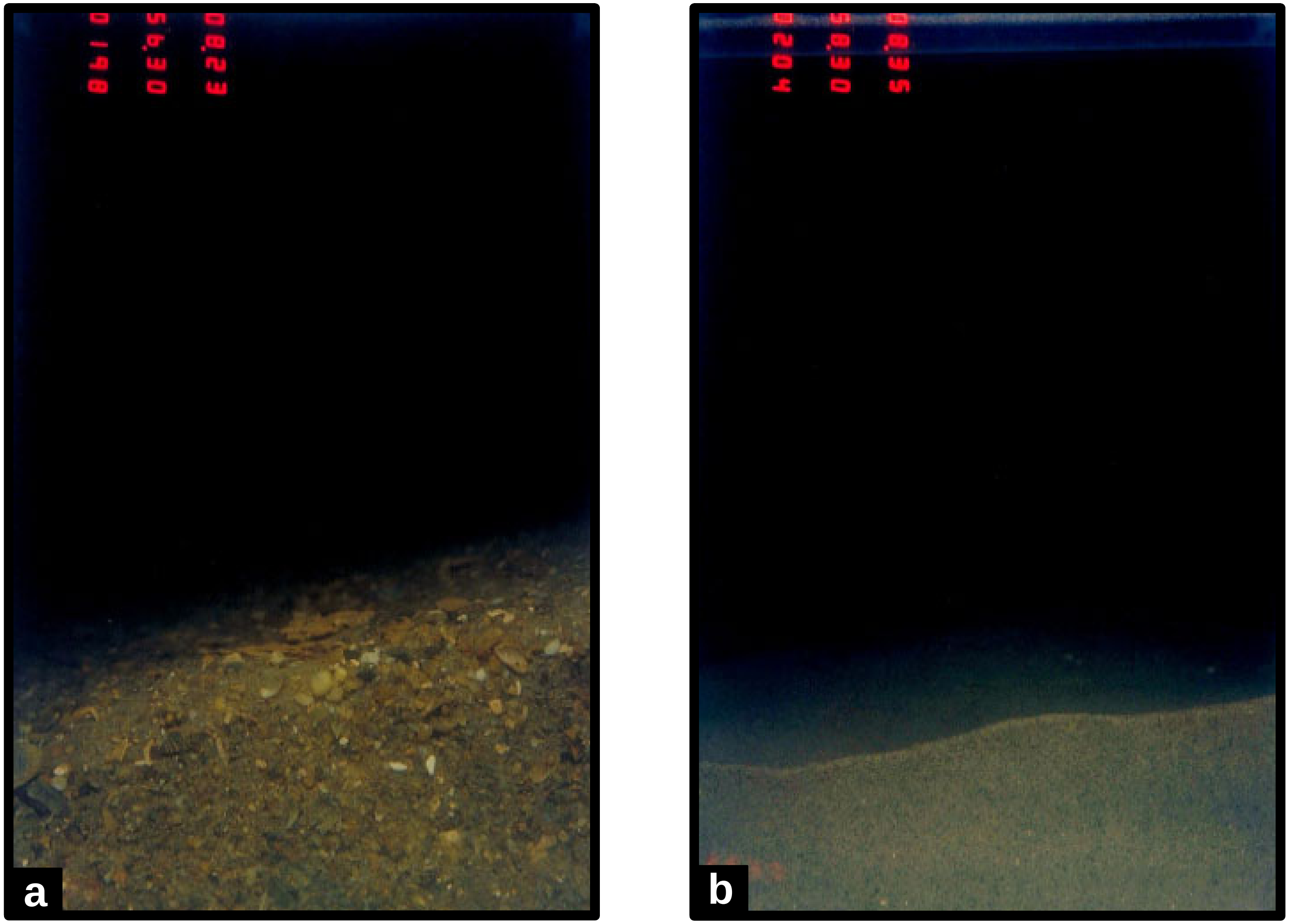

Figure 6-29. a. Sediment profile image from Station 6, Area 3, May 1998, Survey 1 showing the presence of shell fragments and a grain size major mode of 1 to 0 phi (image width represents 15 cm). b. Sediment profile image from Station 7, Area 3, May 1998, Survey 1 showing the presence of bedforms and a grain size major mode of 4 to 3 phi (image width represents 15 cm).

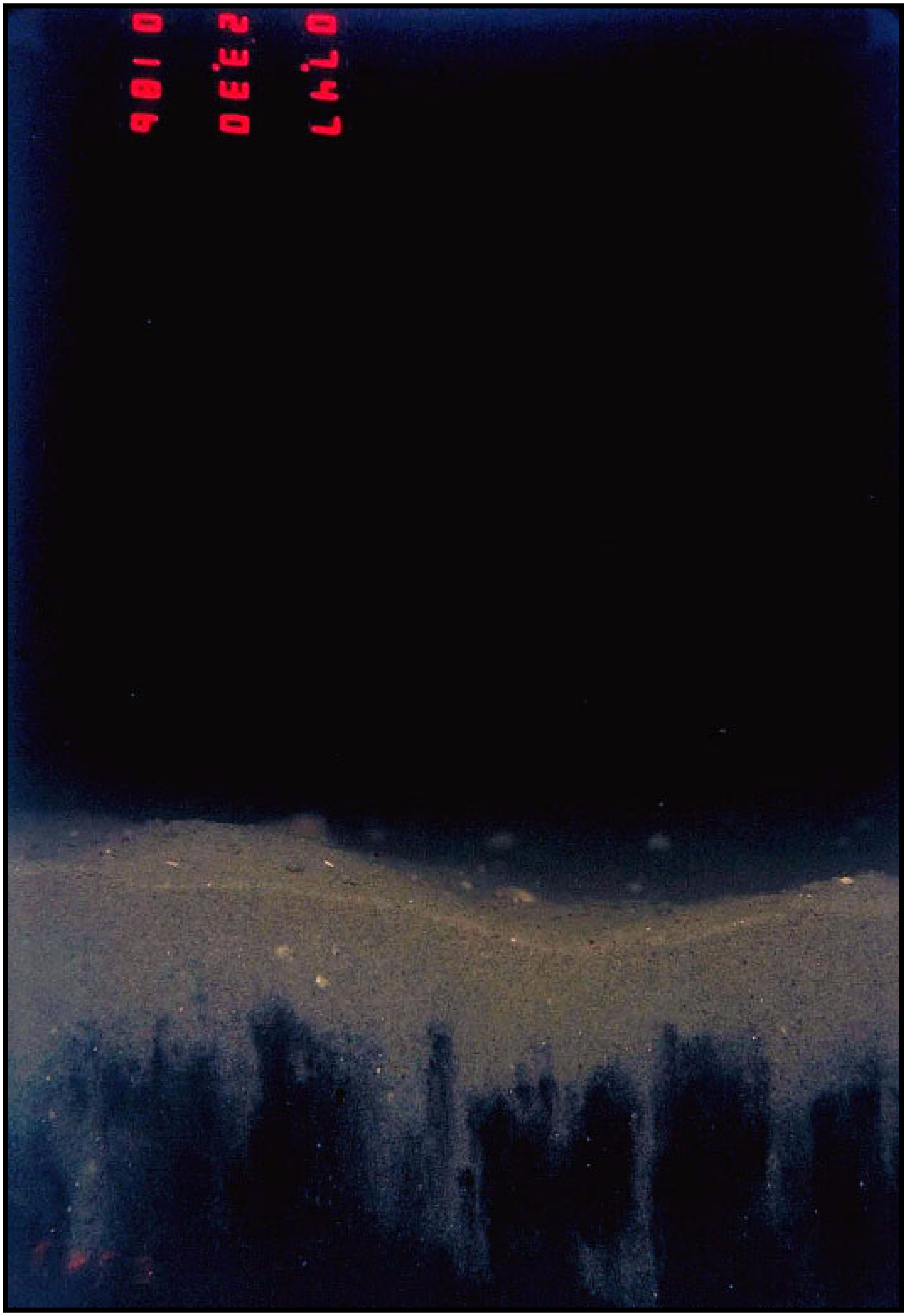

Figure 6-30. Sediment profile image from Station 5, Area 3, May 1998, Survey 1 showing a layer of fine sand on top of a silt/clay foundation (image width represents 15 cm).

There was little evidence of infaunal activity at most of the Area 3 stations, most likely due to a major mode of very fine sand and resulting limited prism penetration than a true paucity of fauna. Station 3 did show evidence at the surface of a feeding depression similar to those made by polychaetes of the genus *Arenicola* (Figure 6-31). Station 2 showed the presence of a polychaete assemblage with large tubes constructed of mud and shell fragments projecting above the sediment-water interface (Figure 6-32).

Although modal sediment types varied among SPI stations during the September survey (Figure 6-28), most were very fine sand (4 to 3 phi). The two images from Station 6 differed most in modal grain size (2 to 1 phi and 1 to 0 phi), indicating small-scale habitat heterogeneity. Prism penetration ranged from 2.2 to 6.2 cm.

Some infaunal activity was observed in 9 of 14 images collected during the September survey in Area 4. Most of this activity was minimal and only a single image (from Station 10) indicated an infaunal successional stage (Stage III).

6.3.3.4 Area 4

During May 1998, 10 SPI stations were sampled in Area 4 in water depths ranging from 20 to 23 m (Figure 6-33). Sediment grain size major mode was uniform throughout the entire area, consisting of very fine sand (4 to 3 phi); bedforms were present throughout the entire area (Figure 6-34). Camera prism penetration ranged from 4.0 to 6.7 cm. While average camera prism penetration was slightly higher in this area than in the other three areas, none of the areas was significantly different from the others in this measure of sediment bearing strength ($p = 0.07$, one-way ANOVA).

A surface diatom layer was evident at Station 5 (Figure 6-35). There was minimal evidence of subsurface biological activity; except for a shallow infaunal burrow at Station 10 (Figure 6-36), most images were devoid of apparent infaunal activity. Other than a thin surface layer (approximately 1 mm) of fine organic material at Station 7 (Figure 6-37), the cross-sectional profile throughout the area resembled very fine beach sand with surface ripples and little or no apparent organic matter in the sediment.

During September 1998, three stations were sampled with the sediment profiling camera (Figure 6-33). The modal sediment type at all stations was very fine sand (4 to 3 phi). Prism penetration ranged from 4.42 to 5.93 cm.

Some biological activity was present in the images from the September survey, but no infaunal successional stages were found. Polychaete tubes and individual bivalves were observed at Station 4. Images from Station 9 showed a patchy diatom film.

6.3.3.5 Adjacent Stations

Two adjacent stations were sampled as part of the May survey. Given that only two images could be collected at each adjacent station (a total of four images), it is difficult to state how representative the images are, considering the relatively dramatic changes in sediment grain size that occurred over relatively short distances in Area 3. Given this caveat, even though prism penetration was similar to the other four areas, Adjacent Station R2 had a noticeably different sediment grain size major mode (2 to 1 phi) as compared to most stations sampled (Figure 6-38).

During the September survey, modal grain size was very fine sand (4 to 3 phi) at Adjacent Station R1. At Adjacent Station R2, modal grain size was 4 to 3 phi in one image and 3 to 2 phi

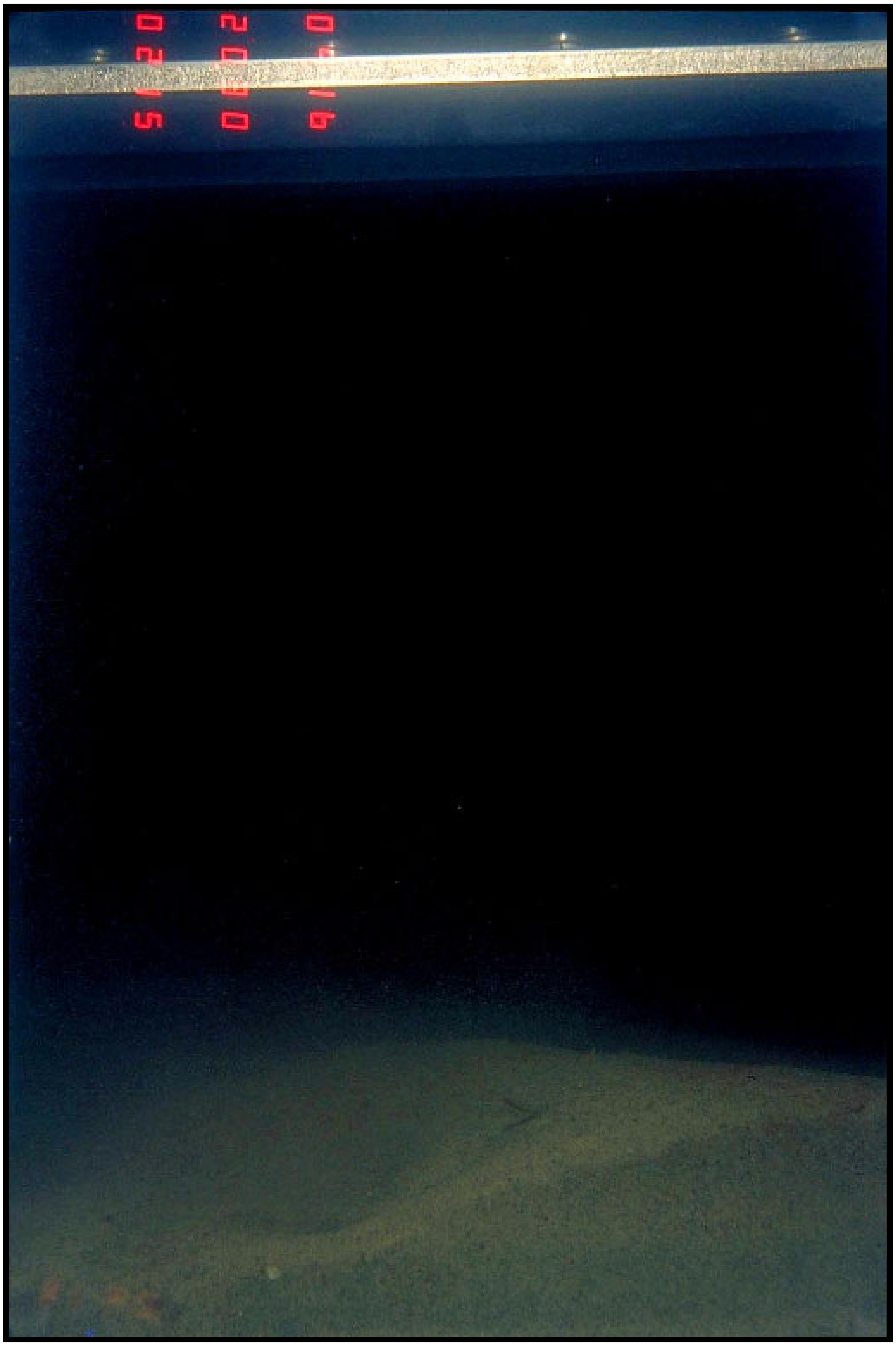

Figure 6-31. Sediment profile image from Station 3, Area 3, May 1998, Survey 1 showing a surface feeding pit most likely caused by an infaunal polychaete with a J-shaped tube (image width represents 15 cm).

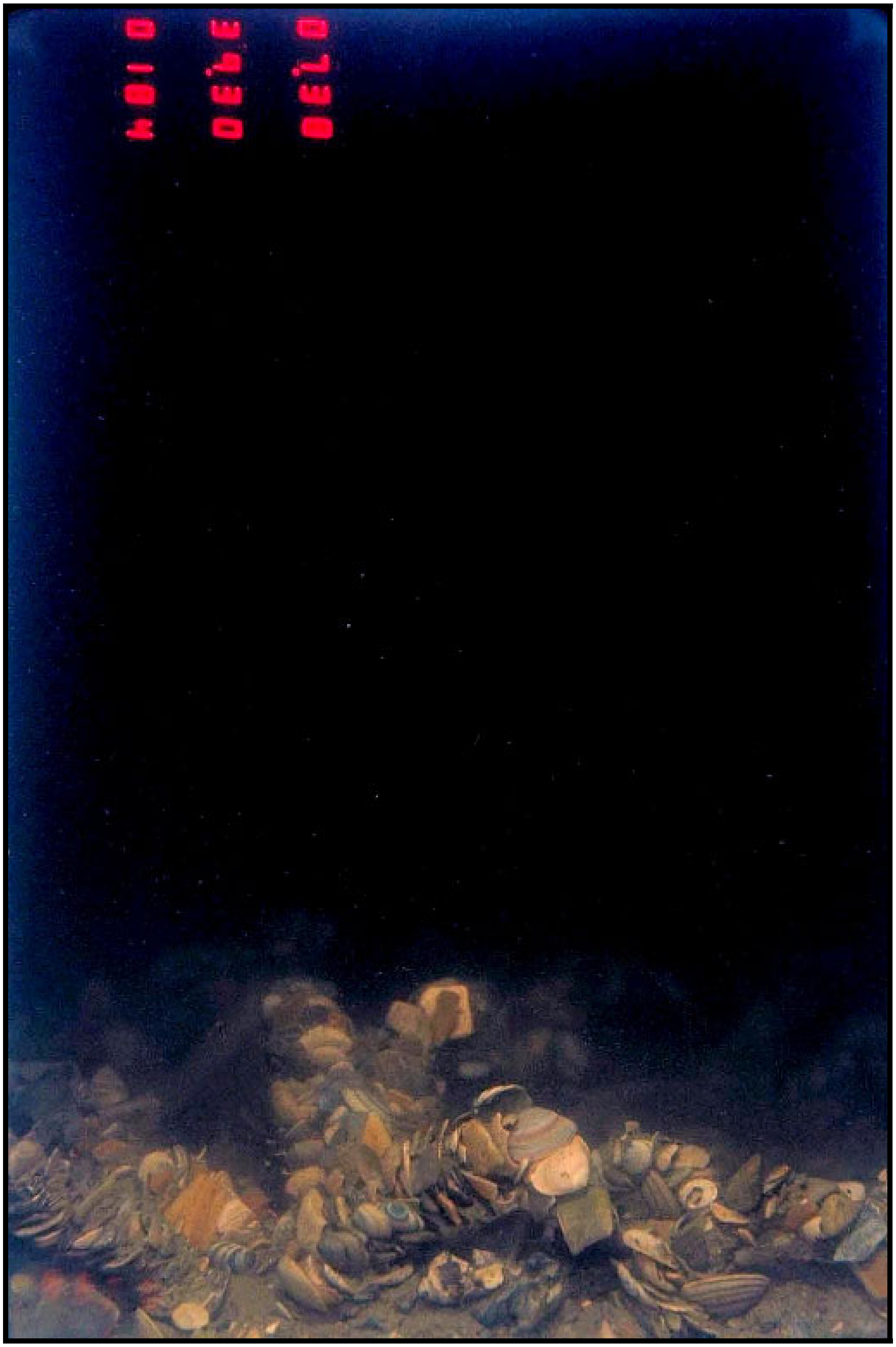

Figure 6-32. Sediment profile image from Station 2, Area 3, May 1998, Survey 1 showing an assemblage of large tubicolous polychaetes with tubes ornamented with shell fragments (image width represents 15 cm).

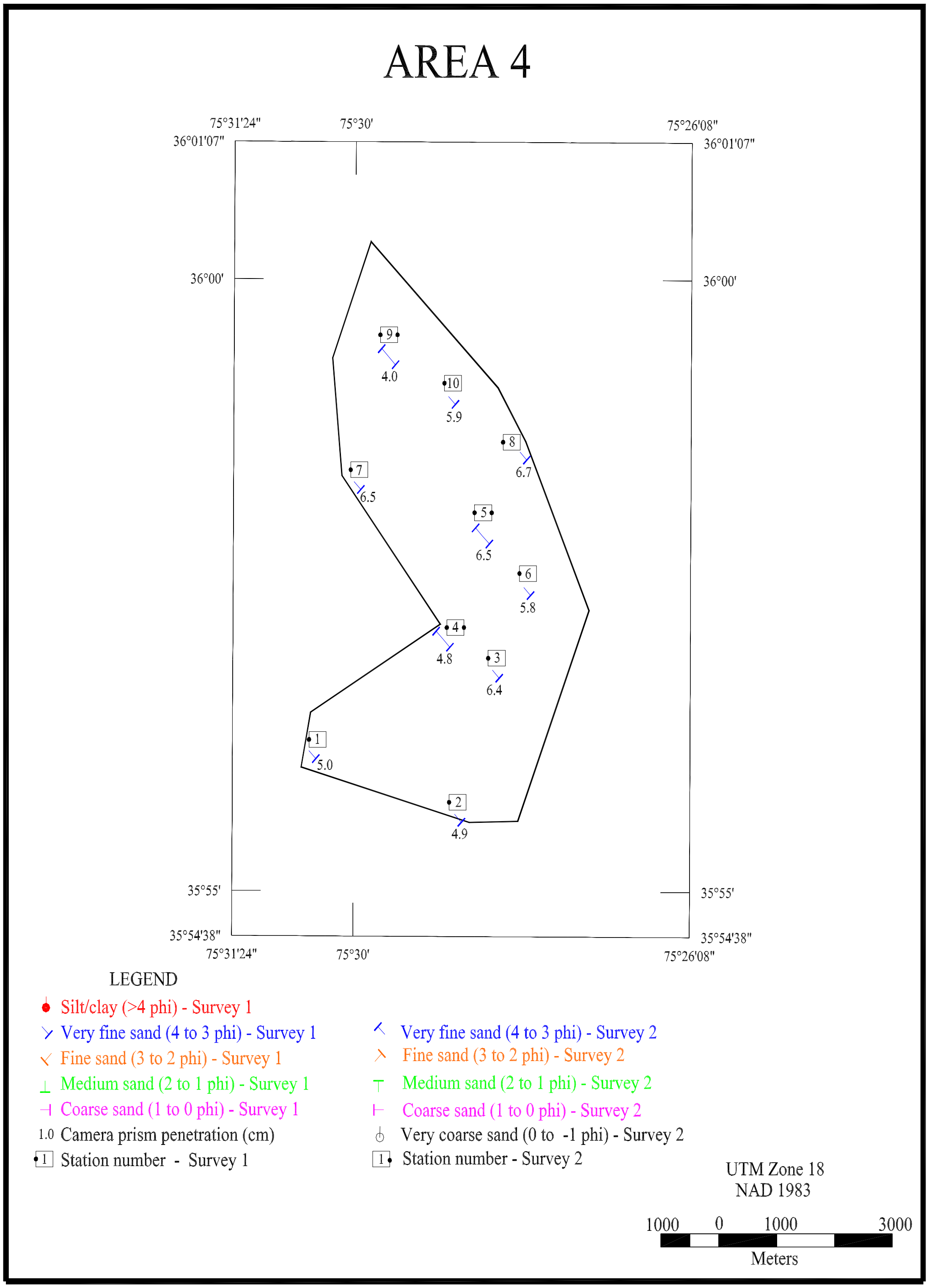

Figure 6-33. Spatial distribution of sediment grain size major mode (Surveys 1 and 2) and camera prism penetration depth (Survey 1) based on sediment profiling in North Carolina Sand Resource Area 4.

Figure 6-34. Sediment profile image from Station 4, Area 4, May 1998, Survey 1 showing a representative image of sediment conditions in the entire area; bedforms were present throughout this region, and all stations had a grain size major mode of 4 to 3 phi (image width represents 15 cm).

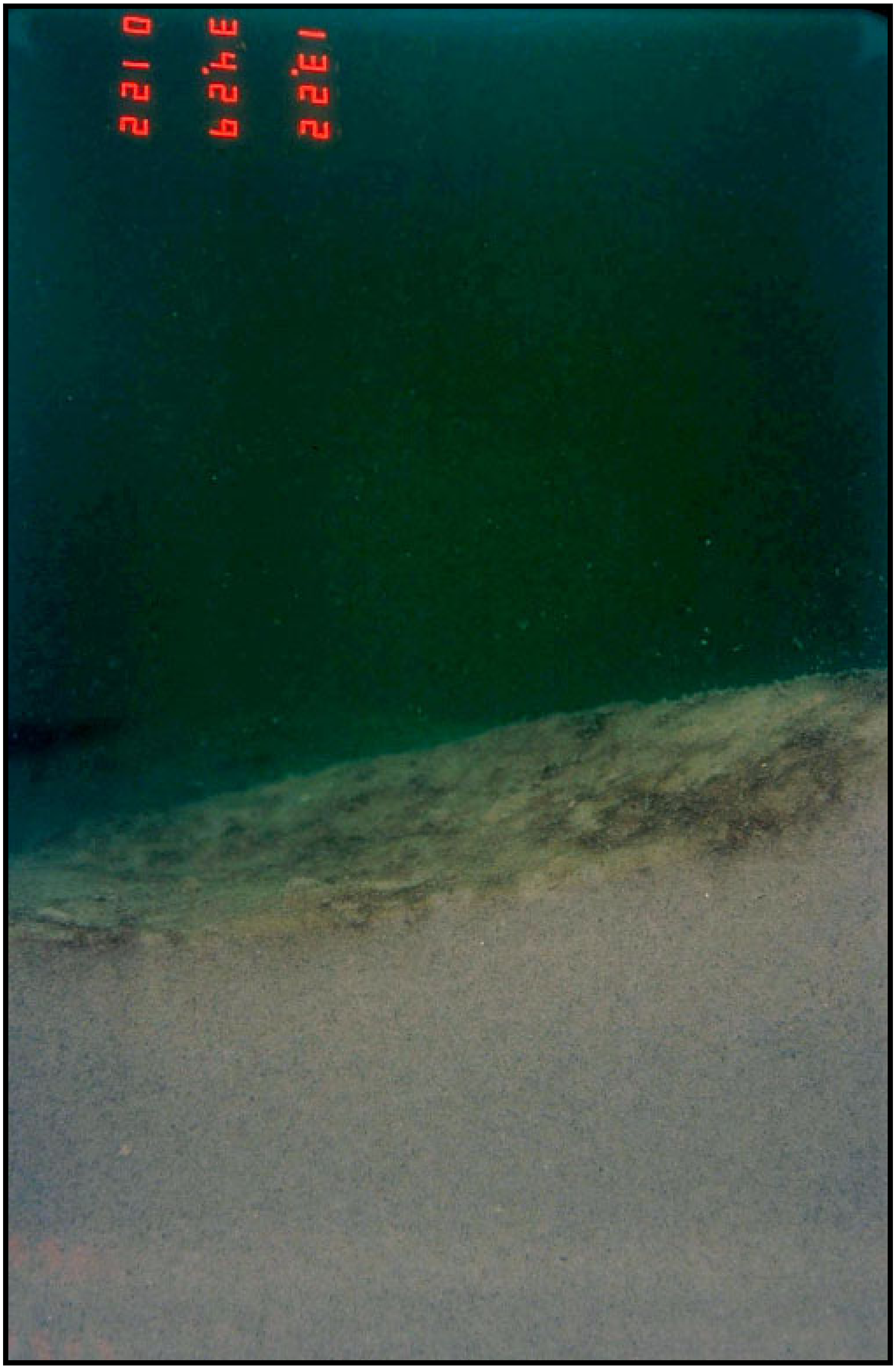

Figure 6-35. Sediment profile image from Station 5, Area 4, May 1998, Survey 1 showing a surface diatom layer (image width represents 15 cm).

Figure 6-36. Sediment profile image from Station 10, Area 4, May 1998, Survey 1 showing a shallow subsurface burrow at the left side of the image (image width represents 15 cm).

Figure 6-37. Sediment profile image from Station 7, Area 4, May 1998, Survey 1 showing a thin depositional layer of fine-grained material on a sandy bottom (image width represents 15 cm).

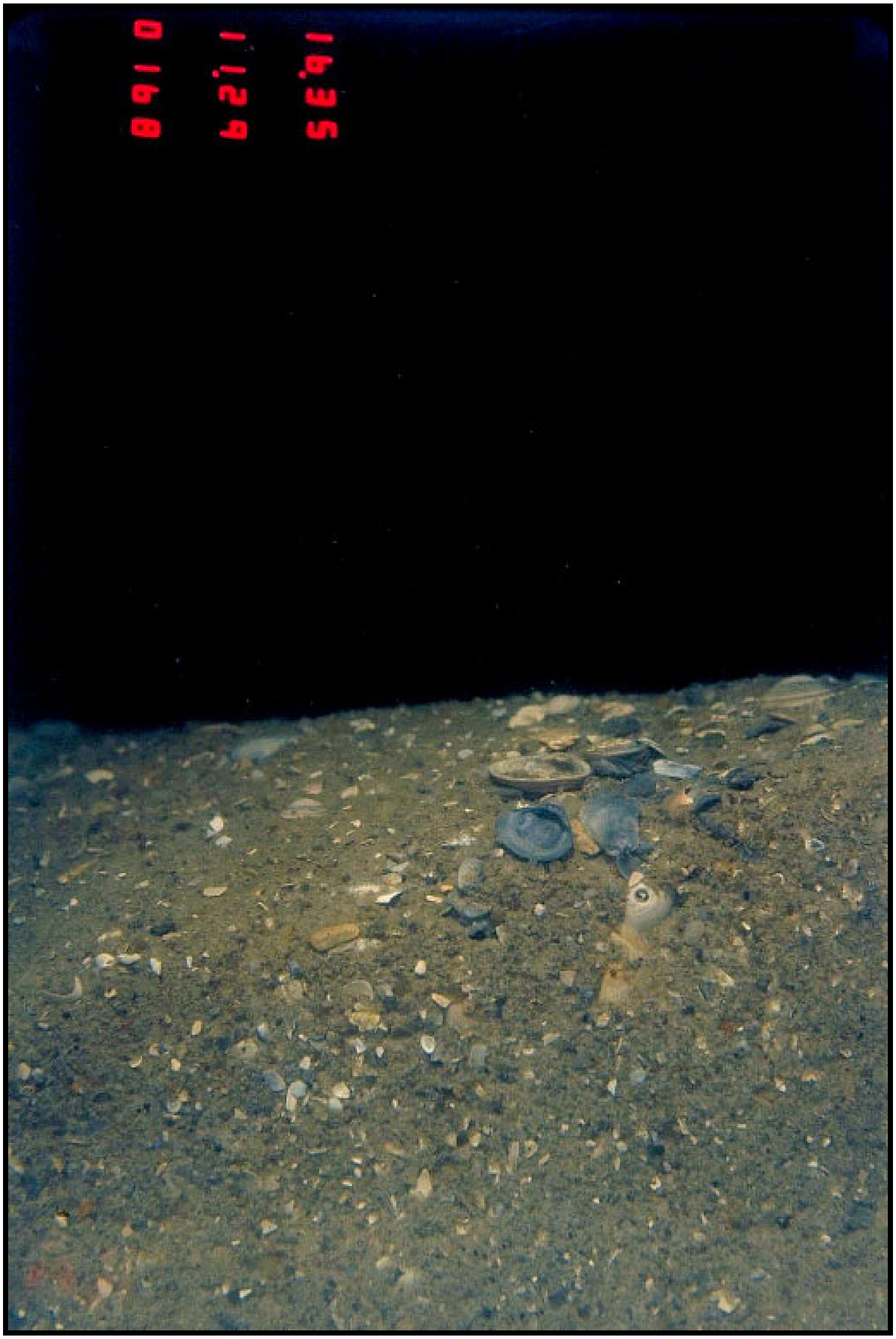

Figure 6-38. Sediment profile image from Adjacent Station 2, May 1998, Survey 1 showing the presence of shell fragments and a grain size major mode of 2 to 1 phi (image width represents 15 cm).

in the other. Prism penetration was higher at Adjacent Station R2 (4.70 and 5.03 cm) than Adjacent Station R1 (2.11 and 3.04 cm). Little biological activity was observed at the adjacent stations during the surveys.

6.3.4 Infauna

A phylogenetic list of infauna collected in bottom grabs during the May and September 1998 surveys is presented in Appendix C5, Table C5-1. Considering both surveys of the sand resource areas, 18,176 individuals were collected, representing 179 taxa in 9 separate phyla. As a group, infauna were more abundant during the September survey, when an average of 321 individuals per grab were collected, as compared to, 106 individuals per grab during the May survey. Sixty-one taxa (34% of total) were common to both surveys. Of those taxa found in just one of the two surveys, 59% (106 taxa) were sampled during the September cruise. The archiannelid *Polygordius* (lowest practical identification level [LPIL]) was numerically dominant in the grabs, especially during the September survey, and represented 14% of all infauna censused over both surveys. Other than *Polygordius*, taxa that were among the top 10 numerical dominants during both the May and September surveys included unidentified oligochaetous annelids and the amphipods *Acanthohaustorius millsi*, *Metharpinia floridana*, *Protohaustorius wigleyi*, and *Pseudunciola obliquua*.

Table 6-3 lists the numerically dominant infaunal taxa sampled from each of the sand resource areas and adjacent stations during the May survey. Numerically dominant taxa sampled during the May survey included the amphipod *P. wigleyi* (16.4% of all collected individuals), unidentified oligochaetous annelids (6.6%), the polychaete *Spiophanes bombyx* (5.2%), the amphipod *M. floridana* (5.1%), and unidentified haustoriid amphipods (4.6%) (Table 6-3). The 10 most abundant taxa collected in grabs during the May survey comprised 57% of all infaunal individuals during that survey.

Numerically dominant taxa collected during the September survey (Table 6-4) were *Polygordius* (15.3% of all individuals collected), the amphipod *P. wigleyi* (10.5%), unidentified cirratulid polychaetes (5.6%), and the amphipods *Byblis serrata* (4.7%) and *P. obliquua* (3.8%). The 10 most abundant taxa collected in grabs during September (Table 6-4) comprised 55% of all infaunal individuals during that survey.

Table 6-5 presents summary statistics for each of the sand resource areas and adjacent stations for the May and September surveys. During the May survey, the mean number of taxa sampled per sand resource station was greatest in Areas 1 (21 taxa) and 3 (20), while Area 1 stations averaged the greatest number of taxa (37) in September. The highest number of infaunal taxa collected from a single station was collected at Station 2 in Area 3 (28 taxa) during the May survey and at Station 6 in Area 3 (52) during the September survey. Area 4 yielded the fewest number of taxa per station during both the May (11 taxa) and September (33) surveys. The fewest number of infaunal taxa collected from a single station was collected at Station 4 in Area 4 (9) during May and at Station 3 in Area 3 (20) during September. The number of taxa yielded by adjacent stations exceeded the averages of each of the sand resource areas during May.

Highest mean number of individuals per station were sampled from Area 3 (station average = 169 individuals) during the May survey, while Area 1 yielded the greatest mean abundances (368) in September (Table 6-5). The highest number of individuals collected from a single station was sampled from Station 10 in Area 3 (361 individuals) during the May survey and from Station 3 in Area 1 (962) in September. Area 2 yielded the lowest mean abundance during the May survey (32), while Areas 4 (233) and 2 (234) yielded the lowest mean

Table 6-3. Ten most abundant infaunal taxa from samples collected during the May 1998 Survey 1 in the four sand resource areas (1, 2, 3, and 4) and two adjacent stations (R1 and R2) offshore North Carolina.

Area	Taxonomic name	Count		Taxonomic name	Count
1	*Spiophanes bombyx*	108	R1	Solenidae (LPIL)	20
	Oligochaeta (LPIL)	97		Spionidae (LPIL)	17
	Metharpinia floridana	80		*Spisula solidissima*	12
	Haustoriidae (LPIL)	61		*Nephtys picta*	10
	Tellina (LPIL)	42		*Byblis serrata*	10
	Apoprionospio pygmaea	29		Lucinidae (LPIL)	6
	Ascidiacea (LPIL)	29		Ostracoda (LPIL)	6
	Polygordius (LPIL)	29		Ampharetidae (LPIL)	5
	Tanaissus psammophilus	28		Nephtyidae (LPIL)	3
	Nephtys bucera	26		*Aricidea wassi*	3
2	*Protohaustorius* (LPIL)	9	R2	*Caulleriella* sp. J	13
	Protohaustorius wigleyi	6		*Protohaustorius wigleyi*	11
	Chiridotea tuftsi	4		*Metharpinia floridana*	9
	Lumbrinerides acuta	4		*Byblis serrata*	6
	Pseudunciola obliquua	4		*Acanthohaustorius millsi*	4
	Tellina (LPIL)	4		*Bathyporeia parkeri*	4
	Bathyporeia parkeri	3		*Pseudoleptocuma minor*	3
	Haustoriidae (LPIL)	3		Oligochaeta (LPIL)	2
	Rhynchocoela (LPIL)	3		*Euspira heros*	2
	Gastropoda (LPIL)	2		*Unciola* (LPIL)	2
3	*Protohaustorius wigleyi*	289	May Total	*Protohaustorius wigleyi*	349
	Spio setosa	75		Oligochaeta (LPIL)	140
	Pseudunciola obliquua	62		*Spiophanes bombyx*	111
	Polygordius (LPIL)	54		*Metharpinia floridana*	109
	Acanthohaustorius millsi	39		Haustoriidae (LPIL)	98
	Oligochaeta (LPIL)	37		*Acanthohaustorius millsi*	85
	Exogone rolani	30		*Polygordius* (LPIL)	84
	Polycirrus sp. G	28		*Spio setosa*	81
	Haustoriidae (LPIL)	28		*Pseudunciola obliquua*	76
	Parapionosyllis longicirrata	22		*Tanaissus psammophilus*	75
4	*Protohaustorius wigleyi*	25			
	Tanaissus psammophilus	25			
	Acanthohaustorius millsi	18			
	Metharpinia floridana	8			
	Pseudunciola obliquua	7			
	Amakusanthura magnifica	6			
	Haustoriidae (LPIL)	6			
	Protohaustorius (LPIL)	5			
	Tellina (LPIL)	4			
	Caulleriella sp. J	3			

LPIL = Lowest practical identification level.

Table 6-4. Ten most abundant infaunal taxa from samples collected during the September 1998 Survey 2 in the four sand resource areas (1, 2, 3, and 4) and two adjacent stations (R1 and R2) offshore North Carolina.

Area	Taxonomic Name	Count	Station	Taxonomic Name	Count
1	*Polygordius* (LPIL)	2033	R1	*Byblis serrata*	73
	Cirratulidae (LPIL)	477		*Ampelisca* sp. X	40
	Byblis serrata	340		*Apoprionospio pygmaea*	34
	Oligochaeta (LPIL)	320		Cirratulidae (LPIL)	23
	Branchiostoma (LPIL)	219		*Nephtys picta*	19
	Tharyx acutus	206		*Tharyx acutus*	14
	Rhynchocoela (LPIL)	184		*Ampelisca* (LPIL)	8
	Protohaustorius wigleyi	167		*Spiophanes bombyx*	6
	Metharpinia floridana	160		*Owenia fusiformis*	6
	Apoprionospio pygmaea	143		Ostracoda (LPIL)	5
2	*Pseudunciola obliquua*	228	R2	*Protohaustorius wigleyi*	77
	Acanthohaustorius millsi	115		*Metharpinia floridana*	54
	Polygordius (LPIL)	78		*Nephtys picta*	27
	Metharpinia floridana	70		*Byblis serrata*	26
	Protohaustorius wigleyi	56		*Ampelisca bicarinata*	25
	Tanaissus psammophilus	49		*Apoprionospio pygmaea*	20
	Cirratulidae (LPIL)	48		*Acanthohaustorius millsi*	19
	Rhepoxynius hudsoni	44		*Pseudunciola obliquua*	18
	Capitella capitata	30		*Caulleriella* sp. J	9
	Acanthohaustorius shoemakeri	28		*Unciola irrorata*	6
3	*Protohaustorius wigleyi*	960	Sept. Total	*Polygordius* (LPIL)	2452
	Apoprionospio pygmaea	365		*Protohaustorius wigleyi*	1679
	Nephtys picta	301		Cirratulidae (LPIL)	906
	Cirratulidae (LPIL)	293		*Byblis serrata*	757
	Polycirrus sp. G	278		*Pseudunciola obliquua*	616
	Ampelisca bicarinata	200		*Apoprionospio pygmaea*	589
	Byblis serrata	161		*Nephtys picta*	571
	Brania wellfleetensis	133		*Metharpinia floridana*	460
	Acanthohaustorius millsi	121		*Acanthohaustorius millsi*	455
	Pseudunciola obliquua	119		Oligochaeta (LPIL)	391
4	*Protohaustorius wigleyi*	418			
	Polygordius (LPIL)	228			
	Pseudunciola obliquua	206			
	Acanthohaustorius millsi	144			
	Byblis serrata	137			
	Metharpinia floridana	123			
	Rhepoxynius hudsoni	119			
	Tanaissus psammophilus	104			
	Tellina agilis	83			
	Nephtys picta	72			

LPIL = Lowest practical identification level.

Table 6-5. Summary of infaunal statistics by survey for sand resource areas (1, 2, 3, and 4) and adjacent stations (R1 and R2) offshore North Carolina.

May 1998 (Survey 1)

Area/ Station	No. of Taxa		No. of Individuals		Density (individuals/m^2)		H' Diversity		J' Evenness		D Richness	
	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation
1	21	4	112	67	1,123	668	2.42	0.33	0.80	0.11	4.49	0.67
2	16	5	32	14	320	141	2.49	0.19	0.92	0.04	4.19	0.89
3	20	7	169	142	1,694	1,417	2.12	0.50	0.73	0.17	3.83	0.95
4	11	2	42	24	420	235	2.04	0.19	0.85	0.06	2.83	0.37
R1	27		119		1,190		2.81		0.85		5.44	
R2	23		69		690		2.66		0.85		5.20	

September 1998 (Survey 2)

Area/ Station	No. of Taxa		No. of Individuals		Density (individuals/m^2)		H' Diversity		J' Evenness		D Richness	
	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation	Mean Per Station	Standard Deviation
1	37	6	368	213	3,685	2,134	2.54	0.44	0.71	0.11	6.22	1.01
2	35	7	234	120	2,344	1,203	2.70	0.41	0.76	0.10	6.39	1.29
3	36	10	350	221	3,503	2,209	2.53	0.30	0.71	0.08	6.20	1.11
4	33	7	233	64	2,334	645	2.58	0.18	0.74	0.05	5.83	1.08
R1	36		285		2,850		2.68		0.75		6.19	
R2	37		339		3,390		2.70		0.75		6.18	

abundances during September. The fewest number of individuals sampled from a single station during the May survey was observed at Station 2 in Area 2 (22 individuals), while the September survey yielded its lowest count from Station 3 in Area 3 (57). Infaunal abundance at adjacent stations was comparable to average abundances of the sand resource areas during both surveys.

A summary of infaunal community indices for each sand resource area is included in Table 6-5 for the May and September surveys. Mean values of species diversity (H') and species richness (J') generally were higher in September as compared to May. Species evenness (D) was similar during both surveys, and this index was less variable across resource areas during September.

Stations in Area 2 yielded the highest mean values of species diversity (2.49) and evenness (0.92) during May (Table 6-5). During the May survey, the highest measure of mean species richness was calculated from Area 1 stations (4.49). The lowest mean values of species diversity and richness (2.04 and 2.83, respectively) during the May survey were found in Area 4. Mean species evenness was lowest in Area 3 (0.73) during the May survey. During September, highest mean values of species diversity, evenness, and richness were found at Area 2 (2.70, 0.76, and 6.39, respectively). Lowest mean values of species diversity, evenness, and richness were recorded during September from Area 3 (2.53), Area 1 and 3 (0.71), and Area 4 (5.83), respectively.

6.3.4.1 Cluster Analysis

Patterns of infaunal similarity among stations were examined with cluster analysis. Cluster analyses excluded those taxa that were rare in the samples or that were redundant (i.e., had a lowest practical identification level [LPIL] designation), except for the polychaete *Mediomastus* (LPIL) and the archiannelid *Polygordius* (LPIL). The majority of taxa included in the cluster analyses were polychaetes (40 taxa), followed by various crustaceans (23), and gastropod (8) and bivalve (4) mollusks.

When examined over both surveys, normal cluster analysis produced four groups (Groups A through D) of stations (samples) that were similar with respect to species composition and relative abundance. Several stations that were not included within any of these 4 station groupings, yet were dissimilar enough not to be grouped together, were placed into an outlier group (Group X). Group X stations were depauperate in terms of abundance and species richness, and included 9 of the 70 stations sampled during the project. Group X was composed of samples collected during both surveys, although primarily it included stations sampled during May. Station Groups C (13 stations) and D (29 stations) included only samples collected during the September survey, while Groups A (2 stations) and B (17 stations) were composed of samples from both the May and September surveys. Figure 6-39 shows the geographic distribution of infaunal stations grouped by normal analysis.

Station Groups A and B were characterized by generally low infaunal abundances. Group A stations supported high numbers of taxa that were rare at all other stations, most prominently the polychaetes *Exogone rolani*, *Parapionosyllis longicirrata*, *Polycirrus* sp. G, and *Spio setosa*. Group C was distinguished from other station groups primarily by the presence of relatively high numbers of the archiannelid *Polygordius* and the polychaetes *Aricidea catherinae*, *A. cerrutii*, *Brania wellfleetensis*, *Hesionura elongata*, *Lumbrinerides acuta*, *Parougia caeca*, and *Streptosyllis arenae*. Group D stations were depauperate with respect to these Group C taxa. In addition, Group D stations yielded taxa that were relatively rare in other stations groups, including the amphipods *Ampelisca* sp. X and *A. bicarinata*, the cumacean arthropod *Cyclaspis*

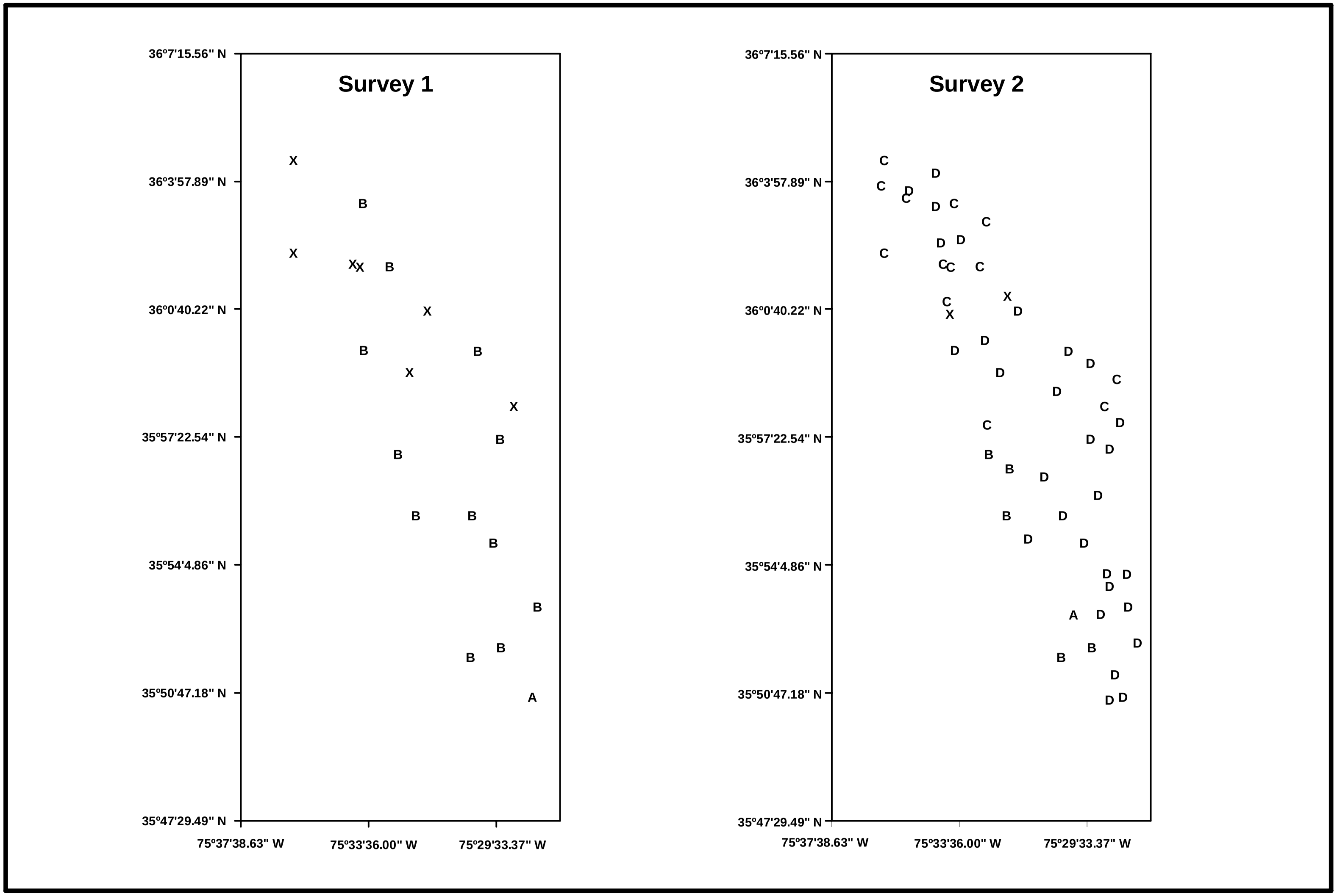

Figure 6-39. Station groups (A to D, and X) based on normal cluster analysis of infaunal samples collected during the May 1998 Survey 1 and September 1998 Survey 2 in the four sand resource areas and two adjacent stations offshore North Carolina.

varians, the gastropod *Natica pusilla*, and the polychaetes *Apoprionospio pymaea* and *S. bombyx*.

Inverse cluster analysis examining both the May and September surveys resulted in four groups of taxa (Groups 1 through 4) that reflected their co-occurrence in resource area samples (Table 6-6). Many infauna included in the overall cluster analysis were relatively rare and heterogeneously distributed; these taxa were not included in the four species groups defined by the inverse analysis. Species Group 1 included the most homogeneously distributed taxa found during the study, both among the various sand resource areas and among surveys. This group included the amphipods *A. millsi*, *M. floridana*, *P. obliquua* and *P. wigleyi*, the polychaete *Caulleriella* sp. J (= *C*. cf. *killariensis*), the bivalve *Tellina agilis*, the archiannelid *Polygordius*, and the tanaid crustacean *Tanaissus psammophilus*. Group 2 taxa primarily comprised various amphipods, including *Acanthohaustrious intermedius*, *Ampelisca* sp. X (= *A*. cf. *verrilli*), *A. bicarinata*, *B. serrata*, *Rhepoxynius hudsoni*, and *Unciola irrorata*, and polychaetes, including *A. pygmaea*, *Owenia fusiformis*, *Nephtys picta*, *S. bombyx*, and *Tharyx acutus*. Species Group 3 included taxa that predominantly were found at a single Area 3 station during each survey, and included mostly polychaetes, including *E. rolani*, *Mediomastus* (LPIL), *P. longicirrata*, *Polycirrus* sp. G, and *S. setosa*. Except for the bivalve *Mytilus edulis*, Species Group 4 was composed entirely of polychaetes, including *A. catherinae*, *A. cerrutii*, *B. wellfleetensis*, *Glycera dibranchiata*, *H. elongata*, *L. acuta*, *P. caeca*, *S. arenae*, and *Scoletoma acicularum*.

Table 6-6. Infaunal species groups resolved from inverse cluster analysis of all samples collected during the May 1998 Survey 1 and September 1998 Survey 2 in the four sand resource areas and two adjacent stations offshore North Carolina.

GROUP 1	**GROUP 3**
Protohaustorius wigleyi	*Spio setosa*
Pseudunciola obliquua	*Parapionosyllis longicirrata*
Acanthohaustorius millsi	*Polycirrus* sp. G
Tanaissus psammophilus	*Exogone rolani*
Metharpinia floridana	*Mediomastus* (LPIL)
Polygordius (LPIL)	*Pista quadrilobata*
Caulleriella sp. J	*Schistomeringos pectinata*
Tellina agilis	*Scoletoma ernesti*
	Lysilla alba
GROUP 2	
Tharyx acutus	**GROUP 4**
Ampelisca sp. X	*Pisione remota*
Apoprionospio pygmaea	*Mytilus edulis*
Byblis serrata	*Brania wellfleetensis*
Nephtys picta	*Aricidea catherinae*
Spiophanes bombyx	*Aricidea cerrutii*
Ampelisca bicarinata	*Streptosyllis arenae*
Unciola irrorata	*Lumbrinerides acuta*
Rhepoxynius hudsoni	*Hesionura elongata*
Owenia fusiformis	*Parougia caeca*
Acanthohaustorius intermedius	*Mooreonuphis pallidula*
Turbonilla interrupta	*Protodorvillea kefersteini*
Pandora inflata	*Glycera dibranchiata*
	Scoletoma acicularum
	Ampharete acutifrons

LPIL = Lowest practical identification level.

Species Group 1 taxa were the most widely distributed among sand resource stations, although certain of the Group 1 taxa (amphipods *A*. *millsi*, *P. obliquua* and *P. wigleyi*) were sparse in Station Group C. Sediments at Group C stations tended to contain high gravel percentages relative to Group D stations. Only 2 of 29 Group D stations had measurable gravel in surficial sediments, otherwise these stations had sand substrata. Species Group 4 included taxa that were associated with Station Group C. Species Group 3 was associated primarily with Station Group A, which included two stations that had the highest percent gravel of any of the sand resource stations.

6.3.4.2 Canonical Discriminant Analysis

Data collected during the two surveys were analyzed using canonical discriminant analysis to determine which environmental parameters most affected the abundance and distribution of infaunal populations. The first two canonical discriminant variates were used to analyze variability among those station groups identified by normal cluster analysis as being similar with respect to species composition and relative abundance. The first canonical variate (CAN1) correlated best with survey (0.8771). The second canonical variate (CAN2) best correlated with the relative percentages of gravel (0.9299) and sand (-0.8030).

The selection of any sand resource area as a sediment source for nourishment projects will be based partly on its environmental characteristics. Patterns of infaunal similarity among stations (normal cluster analysis) and the co-occurrence of taxa within samples (inverse cluster analysis) therefore were examined for each sand resource area. The following describes the results of this area-by-area analysis for each survey, as well as the affinities of the station groups and species groups identified by cluster analyses. Due to the heterogeneity of many taxa distributions, generally low abundances, and relatively limited sampling, only well-defined species groups generated from the inverse analyses are included in the discussion.

6.3.4.3 Area 1

Normal cluster analysis resulted in five station groups in Area 1 (Groups A through E) that were similar with respect to the composition and abundance of infaunal taxa (Table 6-7). Five of the Area 1 stations were placed into outlier Group X due to infaunal assemblage dissimilarity with one another and with stations composing the five station groupings (A through E). Station Group A consisted of a single station from the September survey that yielded high numbers of the archiannelid *Polygordius* and relatively greater densities of taxa that were rare or absent at other Area 1 stations, including the bivalves *Crenella decussata* and *M*. *edulis*, and the polychaetes *G*. *dibranchiata* and *P*. *remota*. Station Group B consisted of three stations from the May survey that yielded a few sparsely distributed taxa. Station Groups C (12 stations) and D (5 stations) composed most of the Area 1 stations during the September survey. Group C stations were distinguished from other stations groups primarily by yielding relatively greater numbers of the amphipod *P*. *obliquua*, bivalve *Tellina agilis*, and polychaetes *A*. *catherinae*, *A*. *cerrutii*, and *B*. *wellfleetensis*. In general, Group C stations yielded greater abundances of the archiannelid *Polygordius* than other Area 1 stations. Group D stations were characterized by relatively greater densities of the amphipods *Ampelisca* sp. X, *B*. *serrata*, and *U*. *irrorata*, and the polychaete *A*. *pygmaea* than were other stations. Station Group E included two stations during the September survey that yielded relatively low abundances of taxa common in other stations during that survey, although this group did yield relatively greater numbers of the polychaetes *N*. *picta*, *Paraprionospio pinnata*, and *T*. *acutus*.

Table 6-7. Two-way table from normal (Station Groups X–E) and inverse (Species Groups 1-4[a]) cluster analysis of infaunal samples collected during the May 1998 Survey 1 (S1) and September 1998 Survey 2 (S2) in Sand Resource Area 1 (A1) offshore North Carolina. Data are presented as total counts for individual taxa.

Taxon	X					A	B			C												D					E		
	S1-A1-8	S1-A1-6	S1-A1-10	S1-A1-20	S1-A1-7	S2-A1-4	S1-A1-1	S1-A1-16	S1-A1-9	S2-A1-11	S2-A1-12	S2-A1-15	S2-A1-10	S2-A1-17	S2-A1-16	S2-A1-13	S2-A1-14	S2-A1-20	S2-A1-3	S2-A1-7	S2-A1-8	S2-A1-1	S2-A1-19	S2-A1-2	S2-A1-18	S2-A1-6	S2-A1-5	S2-A1-9	
Apoprionospio pygmaea	0	28	0	0	0	0	0	0	1	0	0	3	0	0	0	0	0	0	0	0	0	6	9	73	0	51	0	1	1
Ampelisca sp. X	0	0	0	0	0	0	0	0	0	0	2	10	1	3	0	0	0	0	0	1	0	1	42	15	0	47	15	5	
Spiophanes bombyx	0	108	0	0	0	0	0	0	0	3	1	6	3	0	0	2	0	1	1	1	0	4	12	2	7	0	0	0	
Byblis serrata	0	4	0	0	0	0	8	3	2	1	0	3	3	2	11	11	6	2	2	0	0	88	91	26	42	49	0	3	
Nephtys picta	0	0	0	0	0	0	0	0	0	3	2	7	9	1	2	1	0	1	6	1	0	4	3	1	13	19	39	25	
Unciola irrorata	0	2	0	0	0	0	0	0	0	0	1	5	0	3	3	0	1	3	5	0	4	11	10	2	4	21	0	11	
Rhepoxynius hudsoni	0	0	0	0	0	2	0	0	0	22	6	25	22	12	0	0	0	0	0	0	0	4	5	6	0	0	0	1	2
Tanaissus psammophilus	0	0	1	2	0	7	1	14	10	13	5	6	6	7	0	0	16	2	0	1	1	0	0	0	0	0	0	0	
Protohaustorius wigleyi	0	0	1	0	0	1	3	8	6	5	10	35	0	0	2	0	4	0	0	0	0	0	40	1	39	30	0	0	
Acanthohaustorius millsi	0	0	0	0	0	0	7	7	10	0	9	26	2	0	0	0	3	0	0	1	0	2	0	0	13	0	0	0	
Caulleriella sp. J	1	0	0	1	2	0	3	3	3	8	9	16	3	13	5	15	12	1	0	2	1	2	6	0	7	5	0	10	
Tellina agilis	0	0	0	0	0	0	0	0	1	9	23	9	1	7	2	14	6	2	0	5	12	0	0	0	0	2	0	3	
Pseudunciola obliquua	0	1	0	0	0	0	0	1	0	2	3	7	0	5	4	2	8	0	0	0	0	0	0	0	6	7	0	0	
Polygordius (LPIL[b])	0	0	4	1	24	633	0	0	0	47	49	19	244	152	8	94	77	320	178	153	19	4	12	6	4	9	2	3	
Metharpinia floridana	0	0	4	0	10	0	32	8	26	0	0	0	0	0	5	27	40	14	51	17	1	2	0	0	2	1	0	0	
Spio pettiboneae	0	0	0	0	0	0	0	0	0	0	3	0	1	0	10	1	0	3	0	9	6	0	0	0	17	0	5	8	
Tharyx acutus	0	0	0	0	0	0	0	0	0	0	1	2	9	0	1	0	7	0	3	6	16	0	0	32	4	22	103	0	
Ilyanassa trivittata	0	0	0	0	0	3	0	0	0	0	0	2	4	1	0	2	3	2	1	0	0	0	5	0	2	1	15	0	
Paraprionospio pinnata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	8	9	
Reticulocythereis sp. *A*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	10	0	
Solemya velum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	
Polycirrus eximius	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	0	0	0	0	0	0	0	0	0	0	0	0	0	
Crepidula fornicata	0	0	0	0	0	0	0	0	0	0	0	0	0	1	16	0	0	1	0	0	0	0	1	2	0	0	0	1	
Turbonilla interrupta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	2	0	0	0	0	
Nephtys bucera	2	16	0	0	0	0	7	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	
Americhelidium americanum	1	0	0	0	0	0	3	1	1	0	0	0	0	1	0	0	0	0	2	1	0	0	0	0	0	1	0	1	
Aricidea wassi	0	0	0	0	0	0	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	0	0	0	0	
Protohaustorius sp. B	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Cirrophorus lyra	6	0	6	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Ophelia denticulata	1	0	4	4	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Ampharete acutifrons	0	0	0	0	0	0	0	0	0	0	0	0	3	4	0	0	1	0	3	0	0	2	0	0	0	0	0	1	
Capitella capitata	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	3	0	0	0	0	0	0	5	0	0	
Scoletoma acicularum	0	3	0	1	1	0	0	0	0	0	0	0	2	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	
Parapionosyllis longicirrata	0	0	0	0	1	0	0	0	0	0	0	0	6	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	
Aricidea catherinae	0	0	21	0	0	0	0	2	0	0	0	0	71	0	0	0	0	0	49	3	8	0	0	0	0	0	0	0	3
Brania wellfleetensis	0	0	13	3	0	0	0	0	0	0	0	0	24	24	3	11	2	1	25	7	6	0	0	0	0	0	0	0	
Aricidea cerrutii	0	0	0	0	0	0	0	0	0	0	0	1	75	6	0	1	4	0	0	1	13	0	0	0	0	0	0	0	
Streptosyllis arenae	2	0	0	0	0	0	0	1	0	0	0	0	5	5	0	0	0	0	0	8	16	0	0	0	0	0	0	0	
Lumbrinerides acuta	0	0	1	0	0	0	0	0	0	0	0	0	4	0	0	3	0	0	3	0	13	0	0	0	0	0	0	0	
Hesionura elongata	3	0	0	0	0	11	0	0	0	1	0	0	14	0	0	0	0	0	5	49	44	0	0	0	0	0	0	1	
Parougia caeca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	20	33	0	0	0	0	0	0	0	
Mooreonuphis pallidula	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	3	10	0	0	0	0	0	0	0	
Ampelisca bicarinata	0	0	0	0	0	0	0	0	0	1	0	0	0	0	4	1	0	1	0	0	0	31	3	0	6	0	0	0	4
Glycera dibranchiata	0	2	0	0	0	13	0	0	0	0	0	0	0	1	3	0	3	1	0	0	0	1	0	0	0	0	1	2	
Natica pusilla	0	0	0	0	0	7	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	6	3	0	0	1	
Protodorvillea kefersteini	0	0	0	0	1	18	0	0	0	0	0	0	11	3	0	4	0	0	0	1	0	0	0	0	0	0	0	0	
Pisione remota	1	0	0	0	0	67	0	0	0	0	0	0	0	0	0	0	0	0	1	0	6	0	0	0	0	0	0	0	
Mytilus edulis	2	0	0	0	0	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Crenella decussata	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Crassinella lunulata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	8	2	0	0	0	0	0	0	0	0	0	
Pista cristata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	7	0	0	0	0	0	0	0	0	0	0	
Acanthohaustorius shoemakeri	0	0	1	0	0	0	0	0	0	1	1	11	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	
Oxyurostylis smithi	0	0	0	0	0	0	0	0	0	0	5	5	0	0	0	0	0	0	0	1	2	0	0	0	1	0	0	2	
Amakusanthura magnifica	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	5	0	0	
Bathyporeia parkeri	0	0	1	0	0	0	0	0	5	0	0	0	0	0	0	9	2	0	0	1	0	0	0	0	0	0	0	1	
Spisula solidissima	0	0	1	2	0	0	1	2	2	0	0	1	0	0	2	0	2	0	0	1	0	1	0	0	0	0	0	0	
Chiridotea tuftsi	0	0	0	3	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	
Microprotopus raneyi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	3	0	0	0	0	0	0	2	
Pandora inflata	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	
Owenia fusiformis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	0	3	0	1	0	0	
Phyllodoce arenae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	1	2	0	0	0	0	

[a] Due to the heterogeneity of most taxa distributions, generally low abundances, and relatively limited sampling, only well-defined species groups generated from the inverse analyses are numbered.

[b] LPIL = Lowest practical identification level.

Inverse cluster analysis resulted in four groups of taxa (Groups 1 through 4) that reflected their co-occurrence in samples collected in Area 1 (Table 6-7). Species Group 1 included the amphipods *Ampelisca* sp. X, *B*. *serrata*, and *U*. *irrorata*, and the polychaetes *A*. *pygmaea* and *N*. *picta*. Species Group 2 included the most homogeneously distributed taxa in Area 1, including the amphipods *A*. *millsi*, *M*. *floridana*, *P*. *wigleyi*, *P*. *obliquua*, and *R*. *hudsoni*, the bivalve *T*. *agilis*, the gastropod *I*. *trivittata*, the polychaetes *Caulleriella* sp. J, *Spio pettiboneae*, and *T*. *acutus*, the archiannelid *Polygordius*, and the tanaid *T*. *psammophilus*. Group 3 was composed entirely of polychaetes, including *A*. *catherinae*, *A*. *cerrutii*, *B*. *wellfleetensis*, *H*. *elongata*, *L*. *acuta*, *Mooreonuphis pallidula*, *P*. *caeca*, and *S*. *arenae*. Group 4 taxa included the amphipod *Ampelisca bicarinata*, the bivalves *C*. *decussata* and *M*. *edulis*, the gastropod *N*. *pusilla*, and the polychaetes *G*. *dibranchiata*, *P*. *remota, and Protodorvillea kefersteini.*

Station groups in Area 1 were separated entirely according to survey, with Groups X and B composed of May survey stations and Groups A, C, and D consisting of stations sampled during September. Associations of species groups with station groups were apparent, primarily during the September survey. Species Group 1 taxa were most abundant at Group D stations, which mostly had sandy substrata. Species Groups 2 and 3 were associated with Station Group C, which tended to have measurable amounts of gravel. Station 5 sediment was classified as clayey sand and this station yielded an abundance of the polychaete *T*. *acutus* and relatively few amphipods. The bivalve *Solemya velum* was found only in Area 1 at Station 5 during the September survey.

6.3.4.4 Area 2

Normal cluster analysis resulted in three station groups in Area 2 (Groups A through C) (Table 6-8). Group A was composed of a single station during the May survey that was depauperate in terms of infaunal abundance and number of taxa. Group A did yield taxa that were absent at all other stations in Area 2 (the polychaete *Diopatra cuprea* and gastropods *Euspira heros* and *Turbonilla interrupta*). Station Group B was composed of one station from each survey, and was distinguished from other station groups primarily by the presence of the isopod *C*. *tuftsi* and generally low abundances of infaunal taxa. Station Group C consisted of four stations from the September survey that yielded high densities of the amphipods *A*. *millsi*, *A*. *shoemakeri*, *M*. *floridana*, and *P*. *obliquua*, the gastropod *I*. *trivittata*, and the polychaetes *Capitella capitata*, *Caulleriella* sp. J, and *N*. *picta*. Certain taxa were yielded by Group C stations that were not found in Groups A or B, including the amphipods *Metatiron tropakis* and *R*. *hudsoni*, the cumaceans *C*. *varians* and *O*. *smithi*, and the gastropod *R*. *punctostriatus*.

Inverse cluster analysis resulted in two groups of co-occurring taxa (Groups 1 and 2) in Area 2 (Table 6-8). Group 1 included sparsely distributed taxa such as the amphipods *Metatiron tropakis* and *U*. *irrorata*, the bivalve *S*. *solidissima*, the cumaceans *C. varians* and *O*. *smithi*, and the gastropod *Acteocina bidentata*. Group 2 was composed of the most homogeneously distributed taxa in Area 2 and included the amphipods *A*. *millsi*, *A*. *shoemakeri*, *M*. *floridana*, *P*. *obliquua*, and *P*. *wigleyi*, the archiannelid *Polygordius*, the bivalve *T*. *agilis*, the polychaetes *C*. *capitata*, *Caulleriella* sp. J, and *N*. *picta*, and the tanaid *T*. *psammophilus*.

Species Groups 1 and 2 both were associated with Station Group C (September survey). Stations in Group C had sand substrata and yielded many more amphipods than did those Area 2 stations that had measurable gravel, although both Area 2 stations with gravelly sand were sampled during the May survey; therefore, it is unknown the degree to which seasonal differences accounted for variable infaunal assemblage structure between stations.

Table 6-8. Two-way table from normal (Station Groups A–C) and inverse (Species Groups 1 and 2[a]) cluster analysis of infaunal samples collected during the May 1998 Survey 1 (S1) and September 1998 Survey 2 (S2) in Sand Resource Area 2 (A2) offshore North Carolina. Data are presented as total counts for individual taxa.

Taxon	A	B		C				
	S1-A2-2	S1-A2-4	S2-A2-3	S2-A2-1	S2-A2-2	S2-A2-4	S2-A2-5	
Spisula solidissima	0	1	1	0	3	1	1	1
Metatiron tropakis	0	0	0	0	3	1	1	
Cyclaspis varians	0	0	0	1	4	1	0	
Oxyurostylis smithi	0	0	0	1	3	1	0	
Rictaxis punctostriatus	0	0	0	2	1	2	0	
Edotia triloba	0	1	0	1	1	1	0	
Acteocina bidentata	0	0	0	0	2	1	0	
Unciola irrorata	0	0	0	0	1	1	0	
Americhelidium americanum	0	0	0	0	2	0	0	
Protodorvillea kefersteini	0	0	0	0	2	0	0	
Travisia parva	0	0	0	0	1	0	0	
Lumbrinerides acuta	0	0	0	0	1	0	0	
Ampelisca sp. X	0	0	0	3	0	0	1	
Natica pusilla	0	0	0	3	0	0	0	
Spiophanes bombyx	0	0	0	1	0	0	1	
Glycera dibranchiata	0	0	0	1	0	0	1	
Magelona papillicornis	0	0	0	1	0	0	0	
Acteocina candei	0	0	0	1	0	0	0	
Epitonium multistriatum	0	0	0	1	0	0	0	
Listriella barnardi	0	0	0	1	0	0	0	
Pseudoleptocuma minor	0	0	1	0	0	0	0	
Argissa hamatipes	0	0	1	0	0	0	0	
Encope aberrans	0	0	1	0	0	0	0	
Rhepoxynius hudsoni	0	0	0	30	0	0	14	
Byblis serrata	0	0	0	0	0	0	20	
Brania wellfleetensis	0	0	1	0	2	0	3	
Owenia fusiformis	0	0	1	0	0	0	4	
Pista quadrilobata	0	0	0	0	0	0	3	
Scoletoma acicularum	0	0	0	0	0	0	1	
Ampharete acutifrons	0	0	0	0	0	0	1	
Loimia medusa	0	0	0	0	0	0	1	
Phyllodoce arenae	0	0	0	0	0	0	1	
Apoprionospio pygmaea	0	0	0	0	0	0	1	
Pandora inflata	0	0	0	0	0	0	1	
Pagurus longicarpus	0	0	0	0	0	1	0	
Moira atropos	0	0	0	0	0	1	0	
Ptilanthura tenuis	0	0	0	0	0	1	0	
Acanthohaustorius millsi	0	0	0	112	0	3	0	2
Acanthohaustorius shoemakeri	0	0	0	22	2	4	0	
Metharpinia floridana	5	0	2	0	40	28	0	
Protohaustorius wigleyi	3	6	29	11	2	14	0	
Tanaissus psammophilus	8	2	26	6	8	9	0	
Pseudunciola obliquua	0	4	5	158	7	38	20	
Polygordius (LPIL[b])	0	0	7	2	15	1	53	
Ilyanassa trivittata	0	0	0	0	2	17	4	
Tellina agilis	0	0	4	1	4	4	6	
Capitella capitata	0	0	0	10	3	4	13	
Caulleriella sp. J	0	1	0	1	2	5	10	
Nephtys picta	0	0	1	6	2	1	5	
Chiridotea tuftsi	0	1	12	0	0	0	0	
Bathyporeia parkeri	0	3	4	1	5	0	0	
Ancinus depressus	0	0	7	1	5	0	0	
Drilonereis longa	0	1	0	0	0	0	0	
Cyathura polita	0	1	0	0	0	0	0	
Diopatra cuprea	1	0	0	0	0	0	0	
Euspira heros	1	0	0	0	0	0	0	
Turbonilla interrupta	1	0	0	0	0	0	0	

[a] Due to the heterogeneity of most taxa distributions, generally low abundances, and relatively limited sampling, only well-defined species groups generated from the inverse analyses are numbered.

[b] LPIL = Lowest practical identification level.

6.3.4.5 Area 3

Normal cluster analysis resulted in three station groups in Area 3 (Groups A through C). Station Group A included one station from each survey that each yielded less than half of the taxa included in the inverse analysis for Area 3 (Table 6-9). Group A stations did yield several polychaete taxa that were absent in Station Groups B and C, including *B*. *wellfleetensis*, *E*. *rolani*, *P*. *longicirrata*, *Polycirrus* sp. G, *S*. *acicularum*, and *S*. *setosa*. Group B included stations from both the May and September surveys, while Group C was composed only of stations sampled during the September survey. Groups B and C both yielded relatively high numbers of various amphipod taxa that were absent from Group A stations, including *A*. *millsi*, *M*. *floridana*, *P*. *wigleyi*, and *P*. *obliquua*. Group C was distinguished from Group B by yielding high densities of the amphipods *A*. *bicarinata B*. *serrata*, and *U*. *irrorata*, and the polychaetes *A*. *pygmaea*, *N*. *picta*, *Paraprionospio pinnata*, *S*. *bombyx*, and *T*. *acutus*.

Inverse cluster analysis resulted in four groups of co-occurring taxa (Groups 1 through 4) in Area 3 (Table 6-9). Species Groups 1 and 2 included homogeneously distributed taxa, while Groups 3 and 4 included taxa that did not occur at most Area 3 stations. Group 1 was composed entirely of crustaceans, including the amphipods *A*. *millsi*, *M*. *floridana*, *P*. *obliquua*, and *P*. *wigleyi* and the tanaid *T*. *psammophilus*. Group 2 included the amphipods *A*. *bicarinata B*. *serrata*, and *U*. *irrorata* and the polychaetes *A*. *pygmaea*, *N*. *picta*, *Paraprionospio pinnata*, *S*. *bombyx*, and *T*. *acutus*. Species Group 3 taxa were found primarily at a single station during the September survey, including the gastropod *Crepidula fornicata* and the polychaetes *Bhawania heteroseta*, *Lysilla alba*, *P*. *remota*, *Pista quadrilobata*, *Schistomeringos pectinata*, and *Scoletoma ernesti*. Group 4 included the polychaetes *B*. *wellfleetensis*, *E*. *rolani*, *P*. *longicirrata*, *Polycirrus* sp. G, and *S*. *setosa*.

Associations between species groups and particular station groups were apparent in Area 3. Species Group 2 was associated with Station Group C, which consisted of September stations that had sand bottoms. Species Groups 3 and 4 were associated with Station Group 1, which included two stations that had measurable gravel, one of these with gravelly sand and the other with sandy gravel. Species Group 1 included amphipod crustaceans that were distributed across both surveys and across most Area 3 stations. Most Area 3 stations had sand substrata.

6.3.4.6 Area 4

Normal cluster analysis resulted in three station groups (Groups A through C) in Area 4 (Table 6-10). Groups A (1 station) and B (2 stations) included stations from the May survey, while Group C (10 stations) included all stations sampled during the September survey. Station Groups A and B both were characterized by low abundance and taxa richness, although Group A stations did yield taxa not represented in Group B, including the crustaceans *A*. *americanum* (amphipod) and *C*. *tuftsi* (isopod), the bivalve *S*. *solidissima*, and the polychaete *L*. *acuta*. Group B yielded taxa not collected at Group A stations, including the amphipods *A*. *millsi*, *P*. *wigleyi*, and *P*. *obliquua* and the tanaid *T*. *psammophilus*. Station Group C was distinguished from the other station groups by yielding many more taxa and individuals, including several species not collected from Groups A or B (i.e., the May survey). Taxa that were collected only at Group C stations included the amphipods *A*. *bicarinata*, *B*. *serrata*, *R*. *hudsoni*, and *U*. *irrorata*, the archiannelid *Polygordius*, the bivalve *Tellina agilis*, the cumaceans *C*. *varians* and *O*. *smithi*, and the polychaetes *N*. *picta*, *Orbinia riseri*, *P*. *pinnata*, and *S*. *bombyx*.

Inverse cluster analysis resulted in three groups of co-occurring taxa (Groups 1 through 3) (Table 6-10). Group 1 taxa were collected during both surveys, Group 2 taxa were collected

Table 6-9. Two-way table from normal (Station Groups A–C) and inverse (Species Groups 1-4[a]) cluster analysis of infaunal samples collected during the May 1998 Survey 1 (S1) and September 1998 Survey 2 (S2) in Sand Resource Area 3 (A3) offshore North Carolina. Data are presented as total counts for individual taxa.

Taxon	A		B							C									
	S1-A3-2	S2-A3-6	S1-A3-10	S1-A3-13	S1-A3-3	S1-A3-4	S2-A3-3	S2-A3-4	S2-A3-7	S2-A3-2	S2-A3-1	S2-A3-5	S2-A3-10	S2-A3-12	S2-A3-8	S2-A3-11	S2-A3-13	S2-A3-9	
Protohaustorius wigleyi	2	4	251	15	7	14	14	75	70	7	2	9	134	130	195	42	87	191	1
Pseudunciola obliquua	0	0	20	6	34	2	0	15	68	0	0	5	0	3	19	1	3	5	
Acanthohaustorius millsi	0	0	18	3	8	10	10	16	27	0	0	0	40	7	8	1	3	9	
Metharpinia floridana	0	0	4	3	0	0	0	4	16	0	0	2	0	0	0	11	12	6	
Tanaissus psammophilus	0	0	7	5	3	5	6	4	3	0	0	1	0	0	1	0	0	0	
Apoprionospio pygmaea	0	2	0	0	0	0	0	0	8	5	42	93	25	33	52	28	62	15	2
Nephtys picta	2	0	1	7	1	1	3	1	5	7	33	36	43	42	18	34	57	22	
Ampelisca bicarinata	0	2	0	0	0	0	0	0	13	0	1	5	14	69	16	68	6	6	
Polygordius (LPIL[b])	54	10	0	0	0	0	4	3	1	10	5	15	13	8	2	22	9	3	
Byblis serrata	0	0	2	1	0	0	1	1	5	17	4	8	11	5	7	76	16	10	
Tharyx acutus	0	3	0	0	0	0	0	1	1	1	9	23	11	3	6	2	13	21	
Caulleriella sp. J	3	3	3	3	0	0	1	1	1	5	6	5	0	9	0	1	5	0	
Unciola irrorata	0	7	0	0	0	0	0	0	0	1	0	3	0	6	1	6	6	2	
Spiophanes bombyx	0	0	0	2	0	0	1	0	1	3	0	5	8	4	1	2	8	3	
Paraprionospio pinnata	0	0	0	0	0	0	0	0	1	0	0	9	2	2	0	5	4	2	
Unciola serrata	0	0	0	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	
Rhepoxynius hudsoni	0	3	0	0	0	0	0	0	0	2	0	0	4	4	5	0	0	0	
Owenia fusiformis	0	0	0	0	0	0	0	3	0	0	0	0	5	0	4	0	0	2	
Capitella capitata	0	0	0	0	0	0	0	0	0	1	0	0	0	1	3	3	0	0	
Orbinia riseri	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	6	12	
Aricidea wassi	0	0	7	0	0	0	0	0	1	0	0	0	0	0	0	1	4	2	
Caecum pulchellum	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	7	1	
Oxyurostylis smithi	0	0	0	0	0	0	0	4	5	0	1	0	0	1	1	2	2	0	
Cyclaspis varians	0	0	0	0	0	0	0	1	2	0	0	0	0	0	4	2	2	0	
Americhelidium americanum	0	0	0	0	0	0	0	0	2	0	1	0	0	0	1	0	2	1	
Natica pusilla	0	0	0	0	0	0	0	0	1	0	1	3	0	2	1	3	2	0	
Rictaxis punctostriatus	0	0	0	0	0	0	0	0	0	0	2	0	0	1	1	1	1	0	
Crepidula fornicata	0	23	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	3
Schistomeringos pectinata	0	34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Scoletoma ernesti	0	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Lysilla alba	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Pista quadrilobata	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Bhawania heteroseta	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Pisione remota	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Bathyporeia parkeri	0	0	3	0	1	2	0	7	0	0	0	0	0	0	0	0	0	0	
Nephtys bucera	0	0	4	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	
Encope aberrans	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	
Spisula solidissima	0	0	1	1	0	4	0	0	0	0	0	0	0	0	0	1	0	0	
Cyathura polita	0	0	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Acanthohaustorius shoemakeri	0	0	0	0	0	0	0	1	10	0	0	0	0	0	0	0	0	0	
Ancinus depressus	0	0	0	0	0	0	0	6	0	0	0	6	0	0	0	0	0	0	
Chiridotea tuftsi	0	0	0	0	0	0	3	2	0	0	0	0	0	0	0	0	0	0	
Turbonilla interrupta	0	0	0	0	0	0	0	0	0	1	0	0	1	3	0	0	1	3	
Ptilanthura tenuis	0	0	0	0	0	0	0	1	0	2	1	1	1	2	0	0	1	0	
Tellina agilis	0	0	0	0	0	0	3	0	1	0	0	6	0	2	0	0	0	0	
Acanthohaustorius intermedius	0	0	0	0	0	0	1	0	4	1	0	0	0	2	0	0	0	0	
Pandora inflata	0	0	0	0	0	0	1	0	0	1	0	0	1	2	0	0	0	0	
Reticulocythereis sp. A	0	0	0	0	0	0	0	0	0	0	1	6	0	0	0	8	0	6	
Acteocina bidentata	0	0	0	0	0	0	0	0	0	0	6	6	0	1	0	0	1	2	
Acteocina candei	0	0	0	0	0	0	0	0	0	0	0	3	3	1	0	0	0	2	
Ampelisca sp. X	0	0	0	0	0	0	0	0	1	7	8	31	0	0	1	0	0	0	
Onuphis eremita	0	0	0	0	0	0	1	0	0	1	4	1	0	0	0	0	0	0	
Goniada littorea	0	0	0	0	0	0	0	0	0	0	3	2	0	0	0	0	0	0	
Lucifer faxoni	0	0	0	0	0	0	0	1	1	0	2	1	0	0	0	0	0	0	
Brania wellfleetensis	4	133	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
Spio setosa	74	103	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Polycirrus sp. G	28	278	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Parapionosyllis longicirrata	22	89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Exogone rolani	30	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Mediomastus (LPIL[b])	2	8	0	0	0	0	0	0	0	0	1	5	0	0	0	0	0	0	
Ensis directus	2	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	
Scoletoma acicularum	9	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
Ilyanassa trivittata	6	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	
Glycera dibranchiata	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	1	0	

[a] Due to the heterogeneity of most taxa distributions, generally low abundances, and relatively limited sampling, only well-defined species groups generated from the inverse analyses are numbered.

[b] LPIL = Lowest practical identification level.

Table 6-10. Two-way table from normal (Station Groups A–C) and inverse (Species Groups 1-3[a]) cluster analysis of infaunal samples collected during the May 1998 Survey 1 (S1) and September 1998 Survey 2 (S2) in Sand Resource Area 4 (A4) offshore North Carolina. Data are presented as total counts for individual taxa.

Taxon	A	B		C										
	S1-A4-5	S1-A4-4	S1-A4-9	S2-A4-5	S2-A4-8	S2-A4-10	S2-A4-2	S2-A4-3	S2-A4-1	S2-A4-4	S2-A4-7	S2-A4-6	S2-A4-9	
Protohaustorius wigleyi	0	22	0	2	1	28	70	40	105	55	11	45	61	1
Pseudunciola obliquua	0	7	0	0	0	0	21	10	67	29	3	48	28	
Acanthohaustorius millsi	0	13	5	0	0	0	8	22	5	45	11	29	24	
Metharpinia floridana	2	2	1	0	16	0	0	0	56	15	9	27	0	
Byblis serrata	0	0	0	2	66	0	0	0	0	1	63	2	3	
Tanaissus psammophilus	0	11	6	3	16	37	5	7	1	1	4	10	20	
Polygordius (LPIL)	0	0	0	47	81	42	10	8	9	0	9	13	9	
Tellina agilis	0	0	0	14	12	11	2	3	11	2	3	3	22	
Caulleriella sp. J	0	2	1	1	17	10	0	0	6	1	7	0	7	
Ampelisca bicarinata	0	0	0	7	10	2	4	5	2	19	0	7	10	
Nephtys picta	1	0	0	2	24	7	0	9	2	8	5	10	5	
Unciola irrorata	0	0	0	1	9	2	0	1	1	9	9	8	3	
Rhepoxynius hudsoni	0	0	0	15	0	37	7	32	0	0	0	0	28	2
Cyclaspis varians	0	0	0	0	2	4	6	4	8	2	3	3	1	
Spiophanes bombyx	0	0	0	0	1	2	4	5	6	3	2	1	7	
Oxyurostylis smithi	0	0	0	0	0	7	5	5	5	1	0	0	2	
Orbinia riseri	0	0	0	3	11	8	0	0	2	0	1	4	2	
Bathyporeia parkeri	0	2	0	2	2	11	2	1	2	0	1	2	1	
Spio pettiboneae	0	0	0	1	2	4	1	0	0	0	0	2	0	
Paraeupolymnia sp. A	0	0	0	13	1	0	0	0	0	0	0	2	0	
Paraprionospio pinnata	0	0	0	1	1	0	0	2	0	3	0	1	0	
Amakusanthura magnifica	1	1	5	0	0	0	0	0	0	0	0	0	0	3
Pseudoleptocuma minor	2	2	1	0	0	0	0	0	0	0	0	0	0	
Lumbrinerides acuta	4	0	0	0	0	0	0	0	0	0	0	0	0	
Chiridotea tuftsi	3	0	0	0	0	0	0	0	0	0	0	0	0	
Spisula solidissima	1	0	0	0	0	0	0	0	4	0	1	0	0	
Americhelidium americanum	1	0	0	0	0	1	0	0	1	1	0	1	0	
Edotia triloba	0	0	0	0	0	0	0	0	3	0	0	1	0	
Acteocina canaliculata	0	0	0	0	0	0	0	0	2	1	0	0	0	
Paraonis fulgens	0	0	0	0	0	4	0	1	0	0	1	0	1	
Onuphis eremita	0	0	0	2	0	1	0	1	0	0	1	1	1	
Ancinus depressus	0	0	0	0	0	1	0	1	1	0	0	0	0	
Phyllodoce arenae	0	0	0	0	2	0	0	0	1	0	0	1	1	
Brania wellfleetensis	0	0	0	0	5	0	0	0	1	0	0	0	0	
Capitella capitata	0	0	0	0	2	1	0	0	1	0	0	0	0	
Aricidea wassi	0	0	1	0	1	0	0	0	1	0	1	0	1	
Asterias forbesi	0	0	0	0	1	0	0	0	1	0	1	0	0	
Ptilanthura tenuis	0	0	0	0	2	1	0	0	0	0	1	0	0	
Parougia caeca	0	0	0	1	2	0	0	0	0	0	0	0	0	
Acteocina candei	0	0	0	1	0	0	2	3	0	0	0	0	0	
Spiochaetopterus oculatus	0	0	0	0	0	0	1	2	0	0	0	0	0	
Acanthohaustorius intermedius	0	0	0	0	0	0	16	0	0	2	0	0	0	
Owenia fusiformis	0	0	0	0	0	0	4	1	0	1	3	0	0	
Apoprionospio pygmaea	0	0	0	0	0	1	2	0	0	18	1	2	2	
Natica pusilla	0	0	0	0	0	0	0	0	0	2	2	2	1	
Rictaxis punctostriatus	0	0	0	0	1	0	0	0	0	2	0	0	2	
Caecum pulchellum	0	0	0	0	1	0	0	0	1	2	0	0	0	
Turbonilla interrupta	0	0	0	0	0	0	0	0	0	4	1	0	0	
Tharyx acutus	0	0	0	0	0	0	0	0	0	3	0	0	0	

[a] Due to the heterogeneity of most taxa distributions, generally low abundances, and relatively limited sampling, only well-defined species groups generated from the inverse analyses are numbered.

[b] LPIL = Lowest practical identification level.

primarily from the September survey, and Group 3 taxa were collected only during the May survey. Species Group 1 was composed of the most abundant taxa in Area 4, including the amphipods *A. bicarinata*, *A. millsi*, *B. serrata*, *M. floridana*, *P. wigleyi*, *P. obliquua*, and *U. irrorata*, the archiannelid *Polygordius*, the bivalve *T. agilis*, and the polychaetes *Caulleriella* sp. J and *N. picta*. Group 2 taxa included amphipods *B. parkeri* and *R. hudsoni*, the cumaceans *C. varians* and *O. smithi*, and the polychaetes *O. riseri*, *P. pinnata*, and *S. bombyx*. Group 3 taxa were the bivalve *S. solidissima*, the cumacean *Pseudoleptocuma minor*, the isopods *Amakusanthura magnifica* and *C. tuftsi*, and the polychaete *L. acuta*.

Species Group 1 taxa generally were distributed across station groups and, therefore, across surveys. Species Group 2 was associated primarily with Station Group C (September survey) and Species Group 3 was associated with Station Groups A and B (May survey). No relationship between infaunal assemblage type and sedimentary regime was apparent in Area 4; all stations had either sand or slightly gravelly sand.

6.3.5 Epifauna and Demersal Fishes

Trawls taken in the four sand resource areas during the May 1998 Survey 1 yielded very few organisms (Table 6-11). With the exception of several skate (*Raja* sp.) egg cases, only one fish specimen was collected, a spotted hake (*Urophycis floridana*). Four invertebrate taxa were collected, with the sea star *Asterias forbesi* and rock crab (*Cancer irroratus*) the most abundant. Area 3 produced the most specimens, but 32 individuals was considered sparse.

Table 6-11. Epifauna and demersal fishes collected by mongoose trawl during the May 1998 survey of the four sand resource areas offshore North Carolina.

Taxa	Area				Total
	1	2(out)	3	4	
INVERTEBRATES					
Asterias forbesi		3	15	3	21
Cancer irroratus		4	14	1	19
Pagurus sp.			1		1
Ovalipes ocellatus			1		1
FISHES					
Raja egg case		10			10
Urophycis floridana			1		1
INVERTEBRATE TOTALS					
Total Individuals		7	31	4	42
Total Taxa		2	4	2	4
FISH TOTALS					
Total Individuals		10	1		11
Total Taxa		1	1		2
FISH AND INVERTEBRATE TOTALS					
Total Individuals		17	32	4	53
Total Taxa		3	5	2	6

During the September 1998 Survey 2, 316 epifaunal invertebrates represented by 13 taxa and 412 demersal fishes represented by 11 taxa were collected in the four sand resource areas (Table 6-12). The most abundant invertebrate taxa were the sea stars *Asterias forbesi* and *Luidia clathrata*. The most abundant fish taxa included *Stenotomus chrysops*, *Raja* sp. (egg cases), and *Prionotus scitulus*.

The highest number of invertebrate taxa (10) was collected in Area 3 and the lowest number of invertebrate taxa (4) was collected in Area 2 during the September survey. The number of invertebrate taxa per haul averaged 6.6. Area 1 yielded the highest number of fish taxa (7), whereas Area 2 yielded the lowest number of fish taxa (3). The average number of fish taxa collected per haul was 5.0.

The highest number (269) of individuals (fishes and invertebrates combined) was recorded from Area 1 and the lowest number (47) in Area 2 during the September survey. The number of fishes in the trawl tows for the September 1998 survey ranged from 221 in Area 1 to 28 in Area 3 and averaged 82.4. Invertebrate numbers ranged from 100 in Areas 2(out) and 3 to 16 in Area 2(in) and averaged 63.2 individuals per tow.

6.4 DISCUSSION

Benthic assemblages surveyed from sand resource areas offshore North Carolina consisted of members of the major invertebrate and vertebrate groups that commonly occur in the study region. Numerically dominant infaunal groups included numerous crustaceans, echinoderms, mollusks, and polychaetes, while epifaunal taxa consisted primarily of decapods, sea stars, and squid. Demersal fishes collected in trawls within the sand resource areas also were common in previous surveys, including clearnose skate (*Raja eglanteria*), flounder (*Paralichthys* sp.), scup (*Stenotomus chrysops*), and searobin (*Prionotus scitulus*). These species were numerical dominants during the 1998 sand resource area surveys and are among the common demersal taxa that occur in the region (Grosslein, 1976; Sandifer et al., 1980; MMS, 1989).

Canonical discriminant analysis combining May and September infaunal data indicated that the composition of benthic assemblages inhabiting North Carolina resource area stations was affected primarily by survey, and secondarily by sediment type. Normal cluster analysis resulted in Station Groups C (13 stations) and D (29 stations) that were composed only of samples collected during the September survey, indicating seasonal differences in assemblage composition. Temporal variability in infaunal assemblage composition also was evidenced by both qualitative and quantitative community measures. Less than half (34% of total) of the infaunal taxa sampled over the entire project were collected during both the May and September surveys. Most (59%) of the remainder of censused taxa were collected only during the September cruise, resulting in higher mean values of species richness compared to the May survey. Also, infaunal abundance was greater during the September survey (321 individuals/grab) than during May (106 individuals/grab). Greater infaunal taxa richness and individual abundance during September could have been related to either seasonal parameters or other environmental factors that varied independent of season during the survey period. Increased abundance during warmer months has been observed in some amhipod populations inhabiting OCS areas of the Middle Atlantic Bight (Schaffner and Boesch, 1982). It also is possible that survey differences were an artifact of the sampling design used for the North Carolina sand resource areas investigation. During the expanded September sampling effort, more than twice the number of grab samples (50) were collected as were collected during the May survey (20).

Table 6-12. Epifauna and demersal fishes collected by mongoose trawl during the September 1998 survey of the four sand resource areas offshore North Carolina.

Taxa	Area					Grand Total
	1	2(in)	2(out)	3	4	
INVERTEBRATES						
Asterias forbesi	4	11	41	73	4	133
Luidia clathrata	35		26	15	44	120
Loligo pealei	5	3	21	3		32
Pagurus longicarpus	2	1	6	2	1	12
Libinia dubia			5			5
Ovalipes ocellatus	1	1		2		4
Cancer irroratus			1	1	1	3
Mellita quinquiesperforata	1			1		2
Astropecten articulatus					1	1
Callinectes sapidus				1		1
Hyas sp.				1		1
Persephona punctata				1		1
Portunus gibbesii					1	1
FISHES						
Stenotomus chrysops	207	18	21	27	10	283
Raja egg cases	3	12	48	27		90
Prionotus scitulus	2	1			14	17
Paralichthys sp.	3				3	6
Raja eglanteria	2		1	2	1	6
Synodus foetens	3					3
Dasyatis americana	1			1		2
Peprilus triacanthus			2			2
Decapterus punctatus			1			1
Hippocampus erectus			1			1
Urophycis floridana				1		1
INVERTEBRATE TOTALS						
Total Individuals	48	16	100	100	52	316
Total Taxa	6	4	6	10	6	13
FISH TOTALS						
Total Individuals	221	31	74	58	28	412
Total Taxa	7	3	6	5	4	11
INVERTEBRATE AND FISH TOTALS						
Grand Total Individuals	269	47	174	158	80	728
Grand Total Taxa	13	7	12	15	10	24

Results of the North Carolina sand resource area surveys agree with previous investigations that found particular infaunal taxa associated with specific sedimentary habitats (Sanders, 1958; Young and Rhoads, 1971; Pearce et al., 1981; Barry A. Vittor & Associates, Inc., 1985; Weston, 1988; Chang et al., 1992). An infauna-habitat relationship was apparent in the results of the resource area surveys, despite relatively limited sampling in the study area. Canonical correlation analysis indicated that the composition of benthic assemblages inhabiting resource area stations mostly was affected by relative percentages of gravel and sand.

Weston (1988) found that season was less of an influencing factor than sedimentary regime on infaunal assemblage composition in waters offshore North Carolina. Those findings apparently contrast with the sand resource area surveys that found the importance of sediments as secondary to survey, which could imply seasonality. Day et al. (1971) determined that infaunal distribution varies along a depth gradient from the beach zone to the edge of the continental shelf off North Carolina. The turbulent zone includes the inner shelf between 3- and 20-m depths, while a different outer shelf assemblage occurs at between 40 and 120 m. In the Weston (1988) investigation of inner shelf assemblages off Cape Hatteras, infauna were collected quarterly at bottom depths ranging from 23 to 54 m, substantially deeper than those at the sand resource area stations, which ranged from 14 to 24 m. Whether differences in depth of sampling between the sand resource area surveys and the Weston (1988) investigation can account for the apparent difference in the results of the two investigations ultimately is unknown. It simply may be a matter of natural variability of infaunal population recruitment patterns, abiotic parameters, or a combination of both.

Despite a difference in infaunal assemblage composition between surveys, temporal variability may not have been due to ordinary seasonal changes in the distribution and abundance of infaunal populations, if, in fact, such patterns exist. Using Folk's sediment description, which was used to categorize sediments collected with infaunal grabs, the percentage of stations with pure sand (i.e., not slightly gravelly sand or gravelly sand) increased from 20% of the May total (4 of 20 stations) to 66% during September (33 of 50). Complementary SPI data from sand resource area stations indicated that a layer of well sorted, fine sand apparently was deposited over much of the area prior to the September survey, possibly a result of sediment transport and reworking due to Hurricane Bonnie, which passed through the study area during August 1998. Between-survey sedimentary differences apparently were not sufficient to correlate with the first canonical variate in the discriminant analysis. However, change in surficial sediment composition between May and September probably accounted for some of the between-survey differences in infaunal assemblage composition.

Infaunal assemblage distributions therefore likely were a reflection of sediment type distributions during the resource area surveys. Of the four sand resource areas, Area 1 was the most heterogeneous based on normal cluster analysis of the infaunal data (Figure 6-39). Surficial sediments were mixtures of sand and gravel (Folk's description) at about half of the stations in the northernmost resource area (Area 1), as compared to more spatially uniform sand in southern resource areas (Areas 3 and 4). Accordingly, Areas 3 and 4 generally were more spatially homogeneous in terms of infaunal assemblage types delineated by normal analysis. The southernmost resource areas included a few stations with relatively high gravel content but most other stations in these resource areas were characterized by sand substrata (Figure 6-40). Adjacent station assemblages were similar to those at nearby stations within adjacent resource areas during both 1998 surveys.

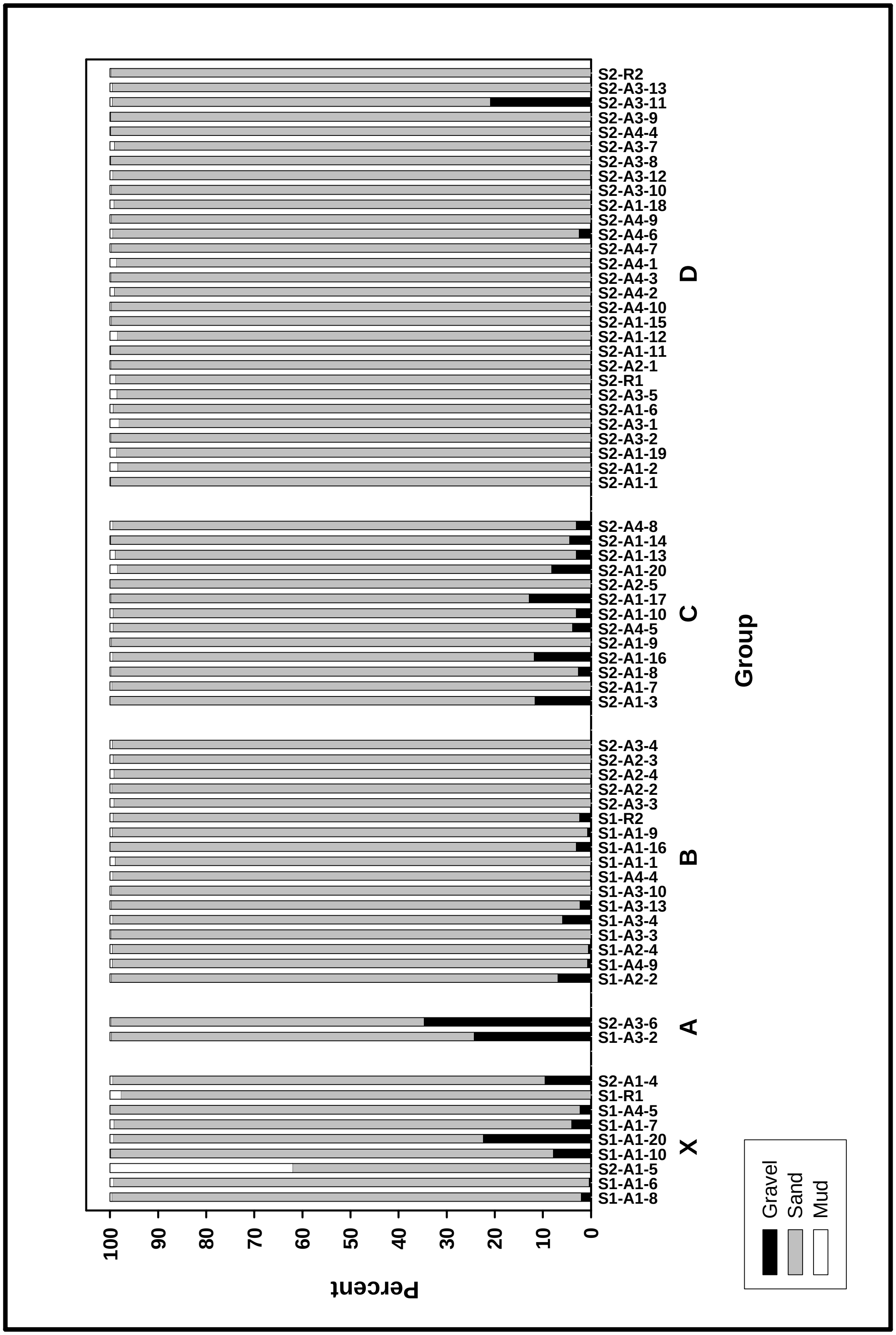

Figure 6-40. Grain size composition of infaunal samples collected during the May 1998 Survey 1 (S1) and September 1998 Survey 2 (S2) in the four sand resource areas (A1, A2, A3, A4) and two adjacent stations (R1 and R2) offshore North Carolina.

Many infaunal taxa collected during the resource area surveys were distributed across a relatively broad sedimentary regime, while others primarily were found at stations with either varied amounts of measurable gravel or pure sand. Infaunal assemblages are composed of taxa that are adapted to particular sedimentary habitats, with foraging effectiveness a key aspect that is closely related to sediment particle size and type (Sanders, 1958; Rhoads, 1974). Ubiquitous taxa in sand resource areas included the amphipods *Byblis serrata* and *Metharpinia floridana*, the archiannelid *Polygordius*, the bivalve *Tellina agilis*, and the polychaetes *Caulleriella* sp. J, *Nephtys picta*, *Paraprionospio pinnata*, and *Spiophanes bombyx*.

Other taxa were associated with narrowly defined sedimentary habitats. Resource area stations with surficial sediments containing measurable gravel yielded some taxa that were rare at sand bottom stations. These gravel-inhabiting taxa included the gastropod *Crepidula fornicata* and the polychaetes *Aricidea catherinae*, *Brania wellfleetensis*, *Exogone rolani*, *Hesionura elongata*, *Parapionosyllis longicirrata*, *Parougia caeca*, *Pisione remota*, and *Polycirrus* sp. G. The numerically dominant archiannelid *Polygordius*, while collected at most resource area stations, was more abundant at stations with sediments containing measurable gravel. Gravel provides interstitial microhabitat for these foraging infauna. Infaunal taxa that were abundant in sand but not in sediments with measurable gravel included the amphipod *Protohaustorius wigleyi*, the polychaete *Apoprionospio pygmaea*, and the tanaid *Tanaissus psammophilus*. Most of the infauna-sediment associations found in the sand resource areas are consistent with observations from other regional benthic investigations (Gardiner, 1976; Pearce et al., 1981; Schaffner and Boesch, 1982; Weston, 1988; Chang et al., 1992).

Several benthic investigations have found that the percentage of very fine sediments (i.e., clay or silt) can be a key determinant of infaunal population distributions, but overall, sediments at resource area stations contained only small amounts of fine sediment during the 1998 surveys. Infaunal assemblage composition in the resource areas would have been different had there been more stations with greater proportions of very fine sediment. One station during the September survey (Station 5 in Area 1) had sediment classified as clayey sand; this station yielded a relatively great abundance of the polychaete *T*. *acutus*, few amphipods, and the deposit feeding bivalve *Solemya velum*. *S*. *velum* was not found at any other resource area station during either of the 1998 surveys.

Results of habitat mapping using SPI data show only some consistency with sediment types defined using sediment texture analysis. The primary limitation when comparing sediment types defined by either method is an inherent absence of definitive knowledge of actual sediment grain size ratios using SPI, especially in areas that have poorly sorted sediments. For example, sediments that are described as slightly gravelly sand using Folk's methodology may be defined simply as fine sand or very fine sand using SPI methods. An example of this disparity is seen in Area 1 during September, when many stations had surficial sediments measured as slightly gravelly sand or gravelly sand, while SPI data from that survey indicated a fairly homogeneous area of very fine sand (Figure 6-10). As indicated above, seemingly minor amounts of gravel or silt in surficial sediments can affect infaunal assemblage composition to a great degree. Taxonomic analysis of infauna collected in Area 1 during September corresponded to sediment texture analysis, with the infaunal assemblage types delineated by normal analysis distributed between stations with sand (Station Group D) and stations with measurable gravel (Station Group C) (Figures 6-39 and 6-40).

Other comparisons between habitats based on infaunal composition, and therefore sediment texture analysis, and those based on SPI analysis are stronger. A clear example of the similarity of results between the two methodologies is evident in Area 3, where SPI data indicated an area of variable sediment texture along a northwest to southeast station line in the southern half of the resource area (Figures 6-28). Sediment texture analysis similarly found varied sedimentary habitats at these Area 3 stations. Normal cluster analysis of infaunal composition at these stations resulted in varied assemblages in this area, with two assemblage types delineated during May and three assemblage types delineated during September (Table 6-9).

A comparison of grain size categories estimated from SPI versus modal, median, and mean grain sizes determined from grab samples during both field surveys shows that the SPI consistently underestimates grain size (Figure 6-41). Most SPI samples fell in the 4 to 3 phi size class, whereas none of median or mean grain sizes from grab samples were above 3 phi. Similarly, none of the modal grain sizes determined from grab samples exceeded 3 phi. These comparisons include SPI and grab samples collected at the same stations, but not at precisely the same location on the seafloor. Thus, some small-scale habitat heterogeneity could lead to observed differences, but it is unlikely that variation would lead to such consistent differences shown in Figure 6-41.

Trawl samples in the sand resource areas indicated depauperate conditions during the May survey. Ultimately, sparse demersal epifauna and fishes yielded during May, along with relatively limited sampling, preclude any definitive statements about possible causes of temporal variability in their abundance and distribution, other than natural variability. Offshore North Carolina, there is considerable variation in the abundance and distribution of epifaunal and demersal fish taxa, both spatially and seasonally (Grosslein, 1976; Wigley and Theroux, 1981; Colvocoresses and Musick, 1984; Ross, 1985; MMS, 1989; Gabriel, 1992), and this dynamic may have been manifest in the results of the sand resource area surveys.

Some patterns of epifaunal and demersal fish distribution and abundance observed during the sand resource area surveys are comparable to historic data. Atlantic rock crab (*Cancer irroratus*), a species known to inhabit inner shelf waters year round (MMS, 1989), was one of the few taxa collected during both the May and September surveys. Demersal fishes collected in trawls within the sand resource areas also were common in previous surveys, including clearnose skate, flounder, inshore lizardfish (*Synodus foetens*), scup, searobin, and southern hake (*Urophycis floridanus*). These fishes are among the common taxa that occur in the region (Grosslein, 1976; Sandifer et al., 1980; MMS, 1989; Gabriel, 1992). Overall, fish abundance was greater during September than during May. This general temporal abundance pattern agrees with the results of previous long-term sampling efforts that found peak fish abundances occur offshore North Carolina during the months of September through November. Scup was the numerically dominant fish taxon (69% of individuals) during the September survey but was not collected during May. This also agrees with historic patterns of distribution; scup tend to aggregate along the shelf break during winter, and occur at all depths on the shelf during summer months (Grosslein, 1976). Overall, trawl contents were not inconsistent with historic regional investigations. Additional information on demersal fish assemblages in and around the four sand resource areas may be contained in the unpublished trawl data set collected by North Carolina Division of Marine Fisheries aboard the R/V DAN MOORE. These data, collected in shelf waters of the state during fall and spring months from 1974 to 1981, were summarized by Ross (1985).

The results of the benthic surveys of the North Carolina sand resource areas agree well with previous descriptions of benthic assemblages residing in shallow shelf waters offshore North Carolina. Overall, canonical discriminant analysis indicated that survey most affected the composition of infaunal assemblages, although sediment texture may have had the greatest influence. Despite inherent spatial and temporal heterogeneity in the distribution and abundance of demersal taxa, results of the 1998 surveys of the sand resource areas generally are consistent with results of historical demersal survey results in the region.

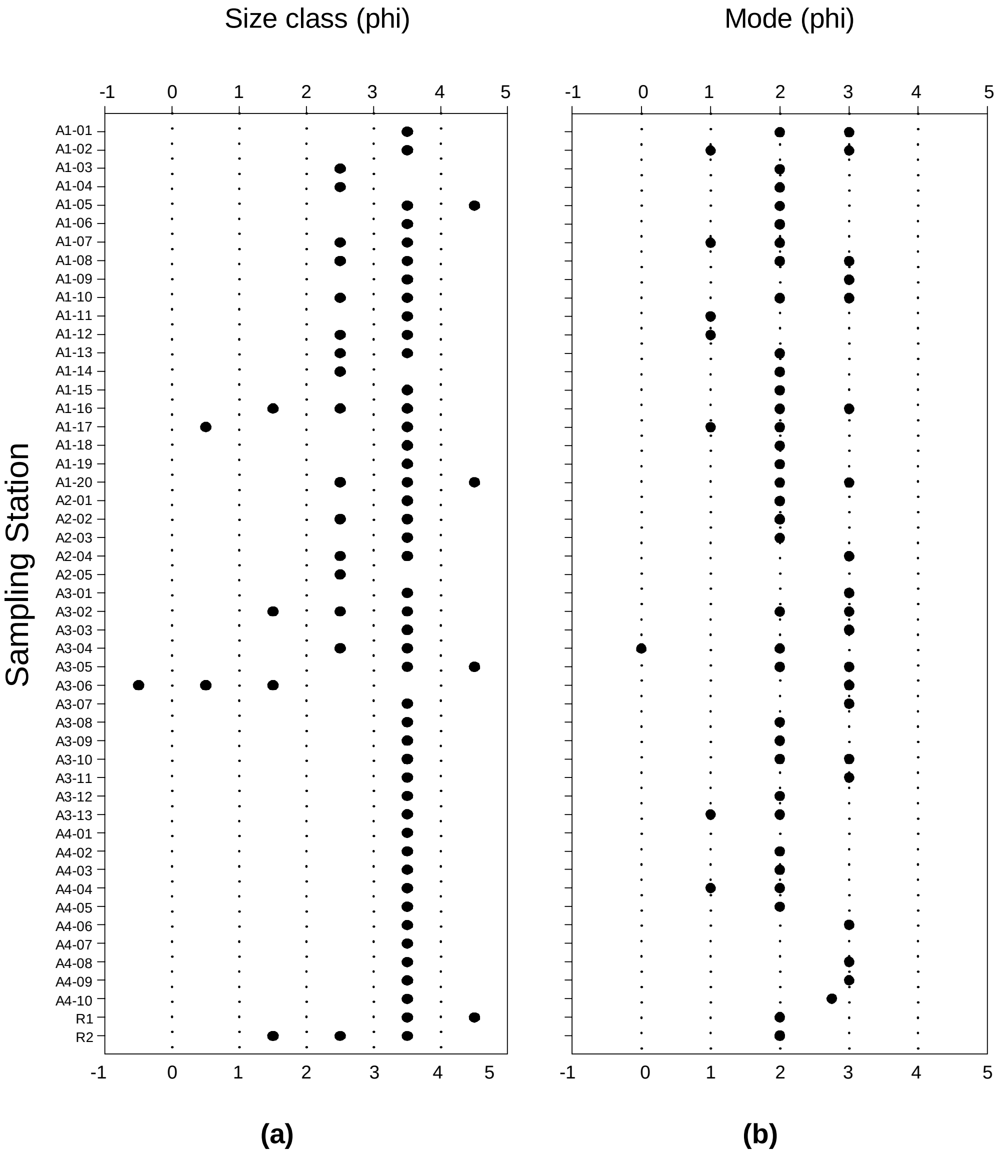

Figure 6-41. Comparison of grain size estimates between sediment profile camera and Smith-McIntyre grabs. (a) Sediment grain size classes plotted for each station sampled by sediment profile camera during the May 1998 Survey 1 and September 1998 Survey 2 offshore North Carolina; (b) modal grain size plotted for each station sampled by Smith-McIntyre grab during the May 1998 Survey 1 and September 1998 Survey 2 offshore North Carolina.

7.0 POTENTIAL EFFECTS

One of the primary purposes of this project is to provide site-specific information for decisions on requests for non-competitive leases from other local, State, and Federal agencies. The information may be used to determine whether or not stipulations need to be applied to a lease. The information also may be incorporated into an Environmental Assessment (EA) or Environmental Impact Statement (EIS), if so required.

Environmental impact analyses of mining operations should be based on commodity-specific, technology-specific, and site-specific information, whenever possible (Hammer et al., 1993). First, the specific mineral of interest and the technological operations for a specific mining operation need to be defined because these two parameters determine the impact producing factors that need to be considered. Once the impact producing factors are known, this information can be translated into statements concerning the impacts that might occur to the full suite of potentially affected environmental resources that may need to be addressed, including geology, chemical and physical oceanography, air quality, biology, and socioeconomics. Then, decisions can be made regarding the type of mitigation necessary to determine the preferred alternative for a specific marine mining operation to acquire project approval.

This section focuses on providing information on potential impacts related to physical processes and biological considerations of sand mining for beach nourishment from four sand resource areas offshore North Carolina. Sand for beach replenishment is the commodity of interest. Two primary dredging technologies are available for offshore sand mining operations, depending on distance from source to project site, the quantity of sand being dredged, and the depth to which sand is extracted at a site (Herbich, 1992). They are: 1) cutterhead suction dredge, where excavated sand is transported through a direct pipeline to shore, and 2) hopper dredge, where sand is pumped to the hopper, transported close to the replenishment site, and pumped to the site through a pipeline from the hopper or from a temporary offshore disposal area close to the beach fill site. As a general rule, cutterhead suction dredging is most effective for projects where the sand resource is close to shore (within 8 km), the dredging volumes are large (>8 MCM), and the excavation depth is on the order of 2.5 to 4 m (Taylor, 1999). Hopper dredging becomes a more efficient procedure when the sand resource areas are greater than 8 km from shore, dredging volumes are relatively small (<2 MCM), and the excavation depth at the sand resource area is less than 2 m (Taylor, 1999). Ultimately, a combination of these factors will be evaluated by dredgers to determine the most cost effective method of sand extraction and beach replenishment for a given project. Availability of dredging equipment also may be a factor for determining the technique to be used; however, the number of cutterhead suction and hopper dredges in operation is about equal in the industry today (Taylor, 1999). As such, both technologies will be evaluated for potential biological effects.

7.1 POTENTIAL SAND BORROW SITES

Four potential sand resource areas were identified offshore North Carolina in Federal waters by the NCGS and MMS. Each area has specific geologic and geographic characteristics that make it more or less viable as a sand resource for specific segments of coast. Areas 1, 2, 3, and 4 contain borrow sites with the greatest potential for use in the future.

All sand resource areas are very similar geologically (medium sand size ridge deposits with relief of 2 m or greater and resource volumes of at least 1 MCM). However, sand from the eastern borrow site in Area 3 (3 east) has a median grain size of 0.21 mm (fine sand), the smallest grain size for any of the potential resource areas. Regardless, all identified potential sand borrow sites are of great interest to the State, primarily due to their proximity to eroding beaches critical for storm protection and recreation. Physical processes (waves and currents) and biological habitat at borrow sites on sand ridges illustrate relatively small variability. However, habitat variability within resource areas varies widely depending on surface area boundaries and geographic position. Although these four potential sand resource areas were designated as ones with greatest potential, it is possible that sand could be dredged from intervening offshore areas.

The amount of dredging that occurs at any site is a function of Federal, State, and local needs for beach replenishment. It is impossible to predict the exact sand quantities needed in the foreseeable future, so a representative value for any given project was estimated based on discussions with State personnel and the MMS. Preliminary analysis of short-term impacts (storm and normal conditions) at specific sites along the coast landward of sand borrow sites indicates that about 1 MCM of sand could be needed for a given beach replenishment event. Long-term shoreline change data suggest that a replenishment interval of about 5 to 10 years may be required to maintain beaches. This does not consider the potential for multiple storm events impacting the coast over a short time interval, nor does it consider longer time intervals absent of destructive storm events. Instead, the estimate represents average change over decades that is a reasonable measure for coastal management applications.

Given the quantity of 1 MCM of sand per beach replenishment event, the surface area covered for evaluating potential environmental impacts is a function of average dredging depth. Two factors should be considered when establishing dredging practice and depth limits for proposed extraction scenarios. First, regional shelf sediment transport dynamics should be evaluated to determine net transport directions and rates. It is more effective to dredge the leading edge of a migrating shoal, and infilling of dredged areas occurs more rapidly at these sites (Byrnes and Groat, 1991; Van Dolah et al., 1998). Second, shoal relief above the ambient shelf surface should be a determining factor controlling dredging depth. Geologically, shoals form and migrate on top of the ambient shelf surface, indicating a link between fluid dynamics, sedimentology, and environmental evolution (Swift, 1976). As such, average shoal relief is a reasonable depth threshold for maintaining environmentally-consistent sand extraction procedures.

A primary question addressed by the modeling efforts relates to sediment transport and infilling estimates at potential borrow sites and the impact of dredging operations on these estimates. Combined wave-current interaction (waves mobilize the seabed and currents transport the sediment) at borrow sites results in a net direction of transport into and out of potential sand resource sites. Historical sediment transport dynamics suggest that the net direction of sediment movement is from north to south, and the rate at which sand moves along the shelf varies.

7.2 WAVE TRANSFORMATION MODELING

Excavation of borrow sites in the nearshore can affect offshore wave heights and the direction of wave propagation. The existence of offshore topographic relief can cause waves to refract toward the shallow edges of borrow sites. This alteration to the wave field by a borrow site may change local sediment transport rates, where some areas may experience a reduction in transport, while other areas may show an increase. To determine the potential physical impacts associated with dredging borrow sites offshore Dare County,NC, wave transformation modeling and sediment transport potential calculations were performed for existing and post-dredging bathymetric conditions. Comparison of results for existing and post-dredging conditions illustrated the relative impact of borrow site excavation on wave-induced coastal processes. Although the interpretation of wave modeling results was relatively straightforward, evaluating the significance of predicted changes for accepting or rejecting a borrow site was more complicated (see Section 4.0 for details).

For existing conditions model results, bottom features offshore the Outer Banks modified wave fields as they propagated shoreward. As an example, wave heights behind the shoal feature in the vicinity of Area 1 were about 0.4 m greater than wave heights at the northern and southern limits of the shoal. The shoal refracted waves, causing a slight focusing of wave energy behind the feature. Because energy was conserved, wave energy focusing behind the shoal caused a reduction in energy at the northern and southern edges of the shoal, producing reduced wave heights in these areas. In addition to the effects of bottom features far offshore, waves were refracted by straight and parallel nearshore bottom contours. For a southeast wave approach (H_{mo} = 1.3 m, T_p = 11.3 sec; see Figure 4-9), waves began to shoal (increase in height) about 500 m offshore and increased in height by 0.2 m before breaking begins. Wave heights were reduced as energy dissipated in the surf zone (about 60 m wide in this example).

Output from post-dredging model runs indicated that wave heights within the borrow site in Area 1 were reduced relative to existing conditions, and this effect was more pronounced in cases that had greater wave heights. Wave fields landward of proposed borrow sites were modified by refraction. As waves propagated across a borrow site (deeper water than the surrounding area), wave refraction guided waves away from the center of the excavation area and toward the shallower edges. The net effect was to create a shadow zone of reduced wave energy (see Figure 4-11) immediately landward of borrow sites and a zone of increased wave energy updrift and downdrift of borrow sites. Because spectral wave model results were used, and because different frequencies in the spectrum were refracted by varying degrees at the borrow site, the regions of increased and reduced wave heights gradually diffused as the wave field approached shore. A result of this energy diffusion was that the length of shoreline affected by a borrow site can be considerably longer than the borrow area.

Another result of the gradual diffusion of wave energy caused by refraction was that borrow sites farther offshore have an impact on a longer length of shoreline; however, the actual magnitude of impact was smaller because the affected wave field had a greater distance to dissipate energy. This result was evident in a comparison of wave energy transformation under identical input wave conditions for Borrow Sites 1 and 2. Site 1 was the larger of the two, but it is located farther offshore. As such, wave height change from existing to post-dredging conditions at the shoreline was less than changes resulting from excavation at Site 2 (see Figure 4-12).

Because model output for storm wave conditions had a significantly longer period than normal conditions, waves were much more responsive to offshore bathymetry gradients. Although the direction of wave propagation was not modified as much as was indicated for normal wave conditions, wave heights changed significantly (e.g., a maximum height of 2.4 m at the southern side of Oregon Inlet) relative to offshore conditions. At offshore shoals directly east of the inlet, wave heights increase approximately 0.7 m over the offshore boundary condition (Figure 4-14). Several shoal areas along the modeled coastline showed similar impacts on wave height, including the area encompassing potential borrow sites. When comparing existing and post-dredging wave height changes under storm conditions, the area of maximum increased wave heights for post-dredging conditions was located at the northernmost corner of Site 1 (see Figure 4-16). The area of maximum wave height decrease also was near Site 1, where wave heights were reduced by 0.12 m. Under these conditions, the length of affected shoreline, to where borrow site shadows propagate, extends approximately 40 km, starting from about 3 km north of Oregon Inlet.

7.3 CURRENTS AND CIRCULATION

Circulation patterns observed throughout the study area were evaluated within the context of potential offshore sand mining operations. Results from this analysis provided estimates of sediment transport potential at proposed offshore borrow sites. Analysis of current meter time series suggested that along-shelf currents possess higher energy than cross-shelf flows. Mean along-shelf flow was directed to the south. Along-shelf currents were dominated by wind-driven processes, accounting for as much as 60% of the total current energy. Wind-driven flows appeared strongly biased by singular events, either local responses to storm winds or non-locally generated buoyant flows, that influenced the magnitude of wind-driven current energy. Although wind-driven currents were less significant in the cross-shelf direction, the largest percentage of cross-shelf energy existed in the wind-driven frequency band. On average, cross-shelf currents were directed offshore. Wave groups and long waves inducing infragravity motions may further contribute to cross-shore current variability.

Previous studies indicated that outflow from the Chesapeake Bay exerts significant influence on current patterns in this region (e.g., Beardsley and Boicourt, 1981). Density-driven flows likely dominated along-shelf surface currents during the May to September time period and enhanced the effects of upwelling-favorable winds. Currents dominated by wind-driven processes were stronger between October to December. In addition to wind-driven currents, high-frequency (noise, random motions) and low-frequency currents were stronger during winter months. This suggested that high- and low-frequency flow processes may be coupled to atmospheric forcing.

Data synthesized in this analysis, and supported by previous studies, suggested that shelf flow was strongest during high-energy wind events, and that near-bottom currents were oriented along the shelf (positive along-shelf currents oriented 340°). Wind-driven, near-bottom currents were oriented along-shelf nearly 40% of the time for the two periods analyzed. This evidence suggested that singular events, with corresponding higher currents, have the greatest potential to transport sand. If so, sediment transport patterns may be predominately in the along-shelf direction, with a net transport oriented in the direction of mean flow. Based on variability analysis, low-frequency (mean) flows were predominantly southwestward. Data also indicated that cross-shelf currents were impacted by northeast wind events, driving downwelling during summer months and offshore flow of the uniform water column during fall and winter. Strong wind events forcing near-bottom offshore flows suggested that cross-shelf sediment transport due to currents may be net offshore.

7.4 SEDIMENT TRANSPORT

Current measurements and analyses, and wave transformation modeling, provided baseline information on incident processes impacting coastal environments under existing conditions and with respect to proposed sand mining activities for beach replenishment. Ultimately, the most important information for understanding physical processes impacts from offshore sand extraction is changes in sediment transport dynamics resulting from potential sand extraction scenarios relative to existing conditions.

Three independent sediment transport analyses were completed to evaluate physical environmental impacts due to sand mining. First, historical sediment transport trends were quantified to document regional, long-term sediment movement throughout the study area using historical bathymetric data sets. Erosion and accretion patterns were documented, and sediment transport rates in the littoral zone and at offshore borrow sites were evaluated to assess potential changes due to offshore sand dredging activities. Second, sediment transport patterns at proposed offshore borrow sites were evaluated using wave modeling results and current measurements. Post-dredging wave model results were integrated with regional current measurements to estimate sediment transport trends for predicting borrow site infilling rates. Third, sediment transport was predicted using wave modeling output to estimate potential impacts to the longshore sand transport system (beach erosion and accretion). All three methods were compared for documenting consistency of measurements relative to predictions, and potential physical environmental impacts were identified.

7.4.1 Historical Sediment Transport Patterns

Regional geomorphic changes between 1862/70 to 1970/96 were analyzed for assessing long-term, net coastal sediment transport dynamics. Although these data did not provide information on potential impacts of sand dredging from proposed borrow sites, they did provide a means of verifying predictive sediment transport models relative to infilling rates at borrow sites and longshore sand transport.

Shoreline position and nearshore bathymetry change documented four important trends relative to study objectives. First, the predominant direction of sediment transport on the continental shelf and along southern Bodie Island was north to south. However, littoral transport between Kitty Hawk and a point about 10 km north of Oregon Inlet was to the north. The greatest amount of shoreline change was associated with beaches adjacent to Oregon Inlet (-2 to -6 m/yr along southern Bodie Island); since 1849/51, southern Bodie Island has migrated to the south at a rate of about 27 m/yr.

Second, the most dynamic features within the study area were the beaches and shoals associated with Oregon Inlet. Areas of significant erosion and accretion were documented for the period 1862/70 to 1970/96, reflecting wave and current dynamics near the entrance and the contribution of littoral sand transport from the north to channel, shoal, and spit migration.

Third, alternating bands of erosion and accretion on the continental shelf east of the Federal-State boundary illustrated relatively slow but steady reworking of the upper shelf surface as sand ridges migrated from north to south. The process by which this was occurring at all resource areas suggested that borrow sites in these regions would fill with sand transported from the adjacent seafloor at rates ranging from 20,000 to 70,000 m^3/yr. For a 2 MCM sand extraction scenario, infilling times for borrow sites in Areas 1 and 2 would be about 30 to 35 years.

Finally, net longshore transport rates determined from seafloor changes in the littoral zone between Kitty Hawk and Oregon Inlet, and nodal point information derived in Section 4.2.2.1, indicated increasing transport rates north and south of a point about 10 km north of the inlet. Net longshore transport near Nags Head was about 160,000 m^3/yr to the north, increasing to about 335,000 m^3/yr near Kitty Hawk. These rates were very consistent with those determined from wave modeling and sediment transport predictions. Just north of Oregon Inlet, net transport rates were determined to be about 354,000 m^3/yr.

7.4.2 Sediment Transport Modeling at Potential Borrow Sites

In addition to predicted modifications to the wave field, potential sand mining at offshore borrow sites resulted in minor changes in sediment transport pathways in and around potential dredging sites. Modifications to bathymetry caused by sand mining only influenced local hydrodynamic and sediment transport processes in the offshore area. Although wave heights changed at the dredged borrow sites, areas adjacent to these sites did not experience dramatic changes in wave or sediment transport characteristics.

Initially, it is anticipated that sediment transport at borrow sites will occur rapidly after sand dredging is completed. For water depths at the proposed borrow sites, minimal impacts to waves and regional sediment transport are expected during infilling. The characteristics of sediment that replaces dredged material during infilling will vary based on location, time of dredging, and storm characteristics following dredging episodes. Average transport rates ranged from a minimum of about 38,000 m^3/yr (Sites 3 east and 4) to a high of about 123,000 m^3/yr (Site 2), while the infilling time varied between 37 to 98 years (see Table 5-4). Site 2 had the greatest infilling rate due to its shallow water depth relative to the other sites and its large perimeter. Because Site 2 is in shallow water, wave-induced currents and background currents were larger than at deeper surrounding sites, and more sediment was mobile in the proximity of the borrow site. Furthermore, sites that have a larger surface area generally will trap more sediment in a given time period. The range of infilling times was based of the volume of sand numerically dredged from a borrow site, as well as the sediment transport rate. Infilling times would have been reduced if storm events were incorporated in the analysis.

Total infilling times were computed using the total design excavated volume divided by the computed infilling rates, and thus represent the length of time required to fill a site that was excavated to the total design depth during a single dredging event. Site 1 has the longest total infilling time, resulting from the large volume extracted from this site and the moderate infilling volume rate computed for the area. Site 3 west has the shortest infilling time due to its small excavation volume, even though it has the smallest infilling rate. The analysis of borrow site infilling time assumed a constant rate of transport from each direction and does not include the effects of modified bathymetry. For example, as a dredged site begins to fill, sediment transport dynamics change. As such, sediment transport rates will fluctuate as a borrow site evolves during infilling. This dynamic process is not simulated in the present analysis. However, the analysis performed provides a reasonable estimate of infilling times for resource management purposes.

7.4.3 Nearshore Sediment Transport Potential

Comparisons of average annual sediment transport potential were performed for existing and post-dredging conditions to indicate the relative impact of dredging to longshore sediment transport processes. Sediment transport potential is a useful indicator of shoreline impacts caused by offshore borrow sites because the computations include the borrow site influence on wave height and direction. Net and gross transport potential were computed using existing wave conditions and post-dredging conditions for two alternate borrow site configurations: 1) Sites 1, 2, 3 east, and 4 modeled together, and 2) Sites 1, 2, 3 west, and 4 modeled together. A plot of gross and net transport potential indicated that there was a reversal in direction of transport along southern Bodie Island (3,970,000 m UTM northing; see Figure 4-17). North of this spot, net transport was to the north, while south of this point to Oregon Inlet, net transport was strongly to the south. The computed north- and south-directed transport potential showed that transport was strongly bi-directional, with a gross transport magnitude of approximately 600,000 m^3/yr far north of Oregon Inlet and a net transport magnitude of only 250,000 m^3/yr. Closer to the inlet, littoral drift became more unidirectional and to the south, with gross and net transport potential magnitudes peaking at over 600,000 m^3/yr.

Difference in longshore transport potential between existing conditions and the two borrow site configurations resulted in a maximum negative change (post-dredging minus existing condition) in computed net sediment transport potential for the second configuration (Sites 1, 2, 3 west, and 4), where the peak change was -34,000 m^3/yr, or 45% of the net transport potential at this point. The maximum positive change was approximately 14,000 m^3/yr or only 8% of the net transport potential computed at this point.

Once the change in sediment transport potential was evaluated between existing and post-dredging conditions, the significance of these changes was determined by applying a significance criterion based on the natural temporal and spatial variability of sediment transport along the modeled coastline. An additional 20 wave model runs were executed to determine the significance criterion envelope. Each of the 20 runs represented a single year of the 20-year WIS hindcast wave dataset. The standard deviation, σ, of sediment transport potential was then computed for the entire coastline. The final determination of dredging significance was made by comparing actual change in transport potential between existing and post-dredging conditions to a significance envelope of one-half the standard deviation ($\pm 0.5\sigma$) along the shoreline (see Figure 4-24). It was determined that no significant changes to longshore sediment transport will result from the modeled borrow site configurations, where borrow Sites 3 west and 3 east were modeled separately. If Sites 3 east and 3 west were dredged simultaneously, the impacts were estimated to exceed the $\pm 0.5\sigma$, and therefore would require mitigation along the affected shoreline or a redesign of the borrow site configuration, likely a reduction in maximum design depth at one of the sites.

7.5 BENTHIC ENVIRONMENT

The purpose of this section is to address potential effects of offshore sand mining on benthic organisms, including analyses of the potential rate and success of recolonization following cessation of dredging. This section is divided into three parts. The first two parts summarize information from the existing literature on effects and recolonization. The first part (Section 7.5.1) describes potential impacts to benthic organisms from the physical disturbance of dredging, which causes removal, suspension/dispersion, and deposition of sediments. The second part (Section 7.5.2) discusses the potential rate and success of recolonization. Finally, the third part (Section 7.5.3) provides predictions of impacts and recolonization relative to the four sand resource areas off North Carolina.

Ecological effects of marine mining and beach nourishment operations have been reviewed by numerous authors (Thompson, 1973; Naqvi and Pullen, 1982; Nelson, 1985; Cruickshank et al., 1987; Goldberg, 1989; Grober, 1992; Hammer et al., 1993; National Research Council, 1995). Effects vary from detrimental to beneficial, short to long term, and direct to indirect (National Research Council, 1995).

Most reviews on the effects of beach nourishment operations have focused on potential impacts at the beach. Comprehensive assessments of the effects on biological resources at open ocean sand borrow sites have been limited (National Research Council, 1995). Alterations to biological resources in offshore sand borrow sites are generally of longer duration, and the consequences of those changes have not been well-defined (National Research Council, 1995). The remainder of this section focuses on potential impacts of dredging operations at offshore sand areas.

7.5.1 Effects of Offshore Dredging on Benthic Fauna

The primary impact producing factor relative to dredging offshore sand borrow sites is mechanical disturbance of the seabed. This physical disruption includes removal, suspension/dispersion, and deposition of dredged material. This section focuses on the potential biological effects of these physical processes on benthic fauna.

7.5.1.1 Sediment Removal

Physical removal of sediments from a borrow site removes benthic habitat along with infaunal and epifaunal organisms that are incapable of avoiding the dredge, resulting in drastic reductions in the number of individuals, number of species, and biomass. Extraction of habitat and biological resources may in turn disrupt the functioning of existing communities. Removal of benthic resources is of concern because they are important in the food web for commercially and recreationally important fishes and invertebrates, and contribute to the biodiversity of the pelagic environment through benthic-pelagic coupling mechanisms. These mechanisms include larval transport and diurnal migrations of organisms, which may have substantial impact on food availability, feeding strategies, and behavioral patterns of other members of the assemblage (Hammer and Zimmerman, 1979; Hammer, 1981).

Removal of sand resources can expose underlying sediments and change the sediment structure and composition of a borrow site, consequently altering its suitability for burrowing, feeding, or larval settlement of some benthic organisms. Many studies show decreases in mean grain size, and in some cases, increases in silt and clay in borrow sites following dredging (National Research Council, 1995). Changes in sediment composition could potentially prevent recovery to an assemblage similar to that which occurred in the borrow site prior to dredging and could by implication affect the nature and abundance of food organisms for commercial and recreational fishery stocks (Coastline Surveys Limited, 1998; Newell et al., 1998). In some cases, dredging borrow sites may create new and different habitat from surrounding substrates, which could result in increased habitat complexity and biodiversity of an area.

The influence of sediment composition on benthic community composition has been recognized since the pioneer studies of Peterson (1913), Thorson (1957), and Sanders (1958). However, more recent reviews suggest that precise relationships between benthic assemblages and specific sediment characteristics are poorly understood (Gray, 1974; Snelgrove and Butman, 1994; Newell et al., 1998). Sediment grain size, chemistry, and organic content may influence recolonization of benthic organisms (McNulty et al., 1962; Thorson, 1966; Snelgrove and Butman, 1994), although the effects of sediment composition on recolonization patterns of various species are not always significant (Zajac and Whitlatch, 1982). Because the complexity of soft-sediment communities may defy any simple paradigm relating to any single factor, Hall (1994) and Snelgrove and Butman (1994) proposed a shift in focus towards understanding relationships between organism distributions and the dynamic sedimentary and hydrodynamic environments. It is likely that the composition of benthic assemblages is controlled by a wide array of physical, chemical, and biological factors that interact in complex ways and are variable with time.

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. Borrow sites have been known to remain well-defined 8 years after dredging (Marsh and Turbeville, 1981; Turbeville and Marsh, 1982). Although nearly 12 years may be required for some offshore borrow sites to refill to pre-dredge profiles, intentionally locating borrow sites in highly depositional areas may dramatically reduce the time for refilling (Van Dolah et al., 1998). In general, shallow dredging (<3 m excavation depth) over large areas causes less harm than small but deep pits, particularly pits opening into a different substrate surface (Thompson, 1973; Applied Biology, Inc., 1979). 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). Deep holes may decrease dissolved oxygen to hypoxic or anoxic levels and increase hydrogen sulfide levels (Murawski, 1969; Saloman, 1974; National Research Council, 1995).

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. Little information exists regarding the relationship between biological assemblages and removal of shoals by dredging. 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. The MMS has funded a study off Maryland and Delaware to address environmental questions concerning use of shoals by fishes and mobile species, potential impacts to these species from offshore sand dredging, and ways to preclude or minimize long-term impacts. 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 one year after dredging disturbance except recovery of average sand dollar weight and biomass composition, which required 2.5 years.

7.5.1.2 Sediment Suspension/Dispersion

Dredging causes suspension of sediments, which increases turbidity over the bottom. This turbidity undergoes dispersion in a plume that drifts with the water currents. The extent of suspension/dispersion depends on the type of dredging equipment, techniques for operating the equipment, amount of dredging, thickness of the dredged layer, sediment composition, sediment transport processes, etc.

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 the 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, that 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 the excavated material is lifted from the bottom by a suction pipe and transferred by pipeline as a slurry (Hrabovsky, 1990; LaSalle et al., 1991). Sediment suspension is caused by the rotating action of the cutterhead and the swinging action of the ladder (Herbich, 1992). A properly operated cutterhead dredge can limit sediment suspension to the lower portion of the water column (Herbich and Brahme, 1991; Herbich, 1992). A well-designed cutterhead, selection of an appropriate cutterhead for a given sediment, the correct relationship between rotational speed of the cutterhead and the magnitude of hydraulic suction, and suitable swing rate of the cutterhead, along with hooded intakes, may reduce turbidity at the cutterhead, although these conditions are rarely achieved (Herbich, 1992). Measurements around properly operated cutterhead dredges show that elevated levels of 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 sediment concentrations in near-bottom waters may be elevated up to 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 the material dredged from the bottom (Herbich and Brahme, 1991). As the hopper dredge moves forward, sediments are 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 sediments. 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; 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 effects 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, floods, hypoxia/anoxia, etc. (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.

Turbidity interferes with the food gathering process of filter feeders and organisms that feed by sight by inundation with nonnutritive particles. Large quantities of bottom material placed in suspension decrease light penetration and change the proportion of wavelengths of light reaching the bottom, leading to decreases in photosynthetic activity. 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 the dredging process. 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). Dredging may produce localized hypoxia or anoxia in the water column due to oxygen consumption of the suspended sediments (LaSalle et al., 1991). Suspension and dispersion processes also uncover and displace benthic organisms, temporarily providing extra food for bottom feeding species (Centre for Cold Ocean Resources Engineering, 1995).

7.5.1.3 Sediment Deposition

Suspended sediments settle and are deposited nearby or some distance from dredged sites. The extent of deposition and the boundaries of biological impact are dependent on the type and amount of suspended sediments and physical oceanographic characteristics of the area.

Dredging effects are not necessarily limited to the borrow site alone. The types of far-field impacts from suspension and deposition of sediments can be detrimental or beneficial. Deposition of sediments can suffocate and bury benthic fauna, although some organisms are able to migrate vertically to the new surface (Maurer et al., 1986). Johnson and Nelson (1985) found decreases in 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 abundance ranging from 34% to 70% at undredged stations within 100 m of a dredged site. Conversely, benthos may show an increase in 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 the 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 nutrients in the water column from simulated storm events in the laboratory (Oviatt et al., 1982), and review of the literature indicating a major restructuring force in infaunal communities is the response of species to resources released from the sediments by periodic disturbance (Thistle, 1981). Fishing also may improve temporarily down current of the dredging site and continue for some months (Centre for Cold Ocean Resources Engineering, 1995).

7.5.2 Recolonization Rate and Success

7.5.2.1 Adaptations for Recolonization and Succession

In dynamic areas that undergo frequent perturbations, benthic invertebrates tend to be small bodied, short lived, and adapted for maximum rate of population increase with high fecundity, efficient dispersal mechanisms, dense settlement, and rapid growth rates (MacArthur, 1960; MacArthur and Wilson, 1967; Odum, 1969; Pianka, 1970; Grassle and Grassle, 1974). In contrast, organisms in stable areas tend to be relatively larger and longer lived with low fecundity, poor dispersal mechanisms, slow growth rates, and adaptations for non-reproductive processes such as competition and predator avoidance. Recolonization of a disturbed area often is initiated by organisms that have the adaptive characteristics for rapid invasion and colonization of habitats where space is available due to some natural or man-induced disturbance. These early colonizers frequently are replaced during the course of succession through competition by other organisms, unless the habitat is unstable or frequently perturbed.

Although the distinction between the adaptive strategies is somewhat arbitrary and is blurred in habitats that are subject to only mild disturbance, the lifestyle differences are fundamentally important because they help explain variations in succession and recolonization rate and success following disturbance (Coastline Surveys Limited, 1998; Newell et al., 1998). Knowledge of faunal component lifestyles allows some predictions of dredging impacts and subsequent recolonization and recovery of community composition (Coastline Surveys Limited, 1998; Newell et al., 1998).

7.5.2.2 Successional Stages

When discussing succession in soft bottom habitats, it is important to point out that most of the past studies have concerned silt-clay bottoms rather than sand habitats. Little is known about succession in sand bottoms of offshore borrow areas.

Successional theory states that organism-sediment interactions result in a predictable sequence of benthic invertebrates belonging to specific functional types following a major seafloor disturbance (Rhoads and Germano, 1982, 1986). Because functional types are the biological units of interest, the succession definition does not rely on the sequential appearance of particular species or genera (Rhoads and Boyer, 1982). This continuum of change in benthic communities has been divided arbitrarily into three stages (Rhoads et al., 1978; Rhoads and Boyer, 1982; Rhoads and Germano, 1982):

Stage I is the initial pioneering community of tiny, densely populated organisms that appears within days of a natural or anthropogenic disturbance. Stage I communities are composed of opportunistic species that have high tolerance for and can indicate disturbance by physical disruption, organic enrichment, and chemical contamination of sediments. The organisms have high rates of recruitment and ontogenetic growth. Stage I communities tend to physically bind sediments, making them less susceptible to resuspension and transport. For example, Stage I communities often include tube-dwelling polychaetes or oligochaetes that produce mucous to build their tubes, which stabilizes the sediment surface. Stage I communities include suspension or surface deposit-feeding animals that feed at or near the sediment-water interface. The Stage I initial community may reach population densities of 10^4 to 10^6 individuals per m^2;

Stage II is the beginning of the transition to burrowing, head-down deposit feeders that rework the sediment deeper with time and mix oxygen from the overlying water into the sediment. Stage II animals may include tubiculous amphipods, polychaetes, and mollusks. These animals are larger and have very low population densities compared to Stage I animals; and

Stage III is the mature and stable community of deep-dwelling, head-down deposit feeders. In contrast to Stage I organisms, these animals rework the sediments to depths of 3 to 20 cm or more, loosening the sedimentary fabric and increasing the water content of the sediment. They also actively recycle nutrients because of the high exchange rate with the overlying water resulting from their burrowing and feeding activities. The presence of Stage III taxa can be a good indication that the sediment surrounding these organisms has not been severely disturbed recently, resulting in high benthic stability and health. Loss of Stage III species results in the loss of sediment stirring and aeration and may be followed by a build-up of organic matter (eutrophication) of the sediment. Because Stage III species tend to have relatively low rates of recruitment and ontogenetic growth, they may not reappear for several years once they are excluded from an area. These inferences are based on past work, primarily in temperate latitudes, showing that Stage III species are relatively intolerant to physical disturbance, organic enrichment, and chemical contamination of sediments. Population densities are low (10 to 10^2 individuals per m^2) compared to Stage I.

The general pattern of succession of benthic species in a marine sediment following cessation of dredging or other environmental disturbance begins with initial recolonization. Initial recolonization occurs relatively rapidly by small opportunistic species that may reach peak population densities within months of a new habitat becoming available after catastrophic mortality of the previous assemblage. As the disturbed area is invaded by additional larger species, the population density of initial colonizers declines. This transitional period and assemblage with higher species diversity and a wide range of functional types may last for years, depending on numerous environmental factors. Provided environmental conditions remain stable, some members of the transitional assemblage are eliminated by competition, and the species assemblage forms a recovered community composed of larger, long-lived, and slow growing species with complex biological interactions with one another.

7.5.2.3 Recolonization Rates

The rate of recolonization is dependent upon numerous physical and biological factors and their interactions. Physical factors include the time of year, depth of the borrow site, water currents and water quality, sediment composition, bedload transport, temperature and salinity, natural energy levels in the area, frequency of disturbance, latitude, etc. Recovery times may be shorter in warmer waters at lower latitudes as compared to colder waters at higher latitudes (Coastline Surveys Limited, 1998; Newell et al., 1998).

Recolonization of borrow sites may occur by transport of larvae from neighboring populations by currents and subsequent growth to adults, immigration of motile species from adjacent areas, organisms contained in sediment slumping from the sides of pits, or return of undamaged organisms from the dredge plume. The rate of recolonization depends on the size of the pool of available colonists (Bonsdorff, 1983; Hall, 1994). Other biological factors such as competition and predation also determine the rate of recolonization and the composition of resulting benthic communities. Timing of dredging is important because many benthic species have distinct peak periods of reproduction and recruitment. Because larval recruitment and adult migration are the primary recolonization mechanisms, biological recovery from physical impacts generally should be most rapid if dredging is completed before seasonal increases in larval abundance and adult activity (Herbich, 1992). Recovery of a community disturbed after peak recruitment, therefore, will be slower than one disturbed prior to peak recruitment (LaSalle et al., 1991).

Benthic recolonization and succession have been reviewed to varying extents for a wide variety of habitats throughout the world (e.g., Thistle, 1981; Thayer, 1983; Hall, 1994; Coastline Surveys Limited, 1998; Newell et al., 1998). Recolonization is highly variable and ranges from within months (e.g., Saloman et al., 1982) to more than 12 years (e.g., Wright, 1977), depending on the habitat type and other physical and biological factors. Focusing on dredging, Coastline Surveys Limited (1998) and Newell et al. (1998) suggested that, in general, recovery times of 6 to 8 months are characteristic for many estuarine muds, 2 to 3 years for sand and gravel, and 5 to 10 years as the deposits become coarser. For offshore dredging of borrow sites in 10 to 20 m water depths for renourishment of Dare County, NC beaches, the USACE (2000) stated that recolonization of affected areas is expected within 2 to 3 years.

The Centre for Cold Ocean Resources Engineering (1995) estimated times for recovery of a reasonable biodiversity (number of species and number of individuals) based on sediment type. In this study, recovery was defined as attaining a successional community of opportunistic species providing evidence of progression towards a community equivalent to that previously present or at non-impacted sites. Fine-grained sediments may need only one year before achieving a recovery level biodiversity, medium-grained deposits 1 to 3 years, and coarse-grained deposits 5 or more years. For a hypothetical borrow site dredging scenario off Ocean City, Maryland, the Centre for Cold Ocean Resources Engineering (1995) stated that virtually all benthic species would be lost, but there may be temporary improvement of fishing due to release of nutrients. Recolonization would start within weeks of closure and moderate biodiversity would occur within one year. The borrow site would be colonized initially by a very different species complex than originally present. An estimate of 2 to 3 years was given for the community to begin to show succession to pre-impact sand habitat species.

Studies of recolonization listed and discussed by Grober (1992) and the National Research Council (1995) indicate that recolonization of offshore borrow sites is highly variable. This variability is not surprising considering the differences between studies in geographic locations, oceanographic conditions, sampling methods and times, etc. Part of the problem in determining recolonization patterns is seasonal and year to year fluctuations in benthic community characteristics and composition. Without adequate seasonal and yearly data prior to dredging, it is difficult to determine whether differences in community characteristics and composition are due to temporal changes or dredging disturbance.

Results and conclusions from these offshore borrow site studies indicate that recolonization usually begins soon after dredging ends. Recolonization periods range in duration from a few months to possibly decades for deep pits. Although abundance and diversity of benthic fauna within the borrow sites often returned to levels comparable to pre-dredging or reference conditions within less than one year, several studies documented changes in benthic species composition that lasted much longer, particularly where sediment composition was altered (e.g., Johnson and Nelson, 1985; Bowen and Marsh, 1988; Van Dolah et al., 1992, 1993; Wilber and Stern, 1992; Barry A. Vittor & Associates, Inc., 1999).

Most recolonization studies of borrow sites concentrated on three main features of infaunal communities, namely the number of individuals (population density), number of species (diversity), and weight (biomass as an index of growth). Dredging is usually accompanied by an immediate and significant decrease in the number of individuals, species, and biomass of benthic infauna. Using biological community parameters (e.g., total taxa, total number of individuals, species diversity, evenness, richness, etc.), previous studies tend to indicate that recovery of borrow sites occurs in approximately one year after dredging. However, these parameters do not necessarily reflect the complex changes in community structure and composition that occur during the recovery process. Major changes in species assemblages and community composition usually occur shortly after dredging such that a different type of community exists. Although the number of individuals, species, and biomass of benthic infauna may approach pre-dredging levels within a relatively short time after dredging, recovery of community composition may take longer.

7.5.2.4 Recolonization Success and Recovery

Assessing impacts of dredging and recolonization and recovery of borrow sites is difficult because most biological communities are complex associations of species that often undergo major changes in population densities and community composition, even in areas that are far removed and unaffected by dredging and other disturbances. Recolonization success and recovery do not necessarily mean that communities should be expected to return to the pre-dredged species composition. To gauge recovery, it is important to compare the community composition of dredged sites with control areas during the same seasons because community composition changes with time.

When long-term alterations in sediment structure and composition occur as a result of dredging, long-term differences in the composition of benthic assemblages inhabiting those sites may occur as well. The recovery time of benthic assemblages after dredging can depend in large measure on the degree and duration of sediment alteration from sand borrowing (Van Dolah, 1996). Recolonization success and recovery also are controlled by compaction and stabilization processes involving complex interactions between particle size, water currents, waves, and biological activities of the benthos following sediment deposition (Oakwood Environmental Ltd., 1999). While the abundance and diversity of infaunal assemblages may recover relatively rapidly in dredged sites, it may take years to recover in terms of sediment and species composition.

One conclusion commonly held is that perturbations to infaunal communities in borrow sites are negligible because organisms recolonize rapidly (Wilber and Stern, 1992). This conclusion often is based on measures including densities, species diversity/evenness indices, relative distribution of classes or phyla, and species-level dendrograms. For example, many researchers have recognized that borrow site and reference area infaunal communities can differ considerably at the species level, although these differences usually are considered insignificant because species diversity is high. According to Wilber and Stern (1992), reliance on these studies may lead to a premature conclusion that impacts to borrow site infauna are minimal because these measures are relatively superficial and ambiguous characteristics of infaunal communities. Wilber and Stern (1992) reexamined infaunal data from four borrow site projects by grouping species into functional groups called ecological guilds based on similarities in feeding mode, locomotory ability, and sediment depth occurrence. Their analyses showed that infaunal communities in borrow and control areas can differ in several ways and that these differences can last several years. Polychaetes and amphipods that recolonize borrow sites are small-bodied and confine their movement and feeding to the surface sediment or the interface between the sediment and water column. In contrast, control areas have well-developed infaunal communities commonly consisting of large-bodied organisms that move and feed deep in the sediment (Wilber and Stern, 1992). They concluded that infaunal communities recolonizing borrow sites may remain in an early successional stage for 2 to 3 years or longer as opposed to being completely recovered in shorter time frames.

The conclusions of Wilber and Stern (1992) coincide with the model of succession discussed previously. The model states pioneering or opportunistic species are the first to colonize an area after a physical disturbance to the bottom (e.g., dredging borrow sites). Pioneering species tend to share several ecological traits, including a tendency to confine activities to the sediment-water interface, possibly because subsurface conditions cannot support a significant number of organisms. The subsurface environment changes with time after the disturbance, possibly by actions of early colonizers, and becomes suitable for deposit feeders and mid-depth burrowers. The relative absence of deposit feeders and mid-depth burrowers is interpreted to mean an area is still in the state of recovery.

Although most of the literature on recolonization rate and success in borrow sites concerns infauna, some information exists for epifauna. The numbers of taxa and individuals collected by trawls in a borrow site off Duval County, Florida greatly exceeded the control area numbers 4 months after dredging and were generally higher 7 and 13 months after dredging (Applied Biology, Inc., 1979). There were no detectable differences between pre-dredging and post-dredging (8 and 16 months) epifaunal communities in a borrow site surveyed by otter trawl and video camera off Egmont Key, Florida (Blake et al., 1995).

7.5.3 Predictions Relative to the Sand Resource Areas

7.5.3.1 Potential Benthic Effects

Sediment Removal

The immediate impact of excavating upper sediments of a sand resource area would be removal of portions of the benthic invertebrate populations that inhabit surficial shelf sediments. Lost individuals would be those with slow-moving or sessile lifestyles, primarily those comprising infaunal populations. Surveys within and adjacent to each of the four North Carolina sand resource areas, as well as benthic investigations of nearby waters, reveal that benthic invertebrate assemblages of inner shelf waters of the study region predominantly are invertebrates, including crustaceans, echinoderms, mollusks, and polychaetous annelids.

The expected loss of benthic fauna due to sediment excavation from the sand resource areas could be considered to represent a negligible impact on the ecosystem when evaluating the impact on a spatial scale. Specific shoals within each resource area are targeted for excavation based on particular sedimentary and bathymetric characteristics, leaving a significant extent of non-dredged areas surrounding the borrow sites. These undisturbed areas would be a primary source of colonizing fauna for the excavated sites (Van Dolah et al., 1984), and would complement colonization of altered substrata via larval recruitment. The great densities and fecundity of invertebrate populations, along with the relatively small areas of impact proposed, would preclude significant long-term negative effects on benthic populations. Impacts most likely would be localized and short-term.

Correlation between sediment composition and the composition of infaunal assemblages has been demonstrated in numerous environmental surveys, including the 1998 surveys of the North Carolina sand resource areas. Invertebrate populations inhabiting marine soft bottoms offshore North Carolina exhibit heterogeneous distributions that largely are the result of local sedimentary regime. Modification of surficial sediments and local bathymetry could result in an alteration of the areal extent and relative distribution of infaunal assemblage types by altering the distribution of sediment types capable of supporting those assemblages.

It is possible that a change in the composition of surficial sediments within excavated areas could become a long-term result of dredging. Several factors could contribute to such an outcome, primarily the type of sediments exposed by dredging, the degree of deposition of fine sediments into dredged sites, and bathymetric alteration that results in hypoxic or anoxic conditions. These factors would depend primarily on the depth of excavation, which would be determined by the vertical relief of the sand shoal to be excavated, the vertical extent of those sediments suitable for coastal nourishment projects, and the volume of sand required.

Because the inner shelf ecosystem of the Middle Atlantic Bight exhibits some heterogeneity in sediment types and their associated assemblages, those infaunal assemblages that initially colonize dredged sites likely would be similar to some naturally occurring assemblages that inhabit nearby non-dredged sites, especially areas with finer sediments. When viewed within a context of scale, removal of sediments from portions of the North Carolina inner continental shelf would at most minimally alter the existing spatial balance of habitat (sediment) types. Moreover, those habitats that have relatively high amounts of finer sediments are not uninhabitable, or necessarily less functional in an ecological sense, when compared to sand or gravel substrata. Various sedimentary habitats merely differ in their level of suitability for certain types of infaunal taxa. Changes in habitat suitability that result from sand removal likely would be ephemeral and inconsequential in the shelf ecosystem, a system where both infaunal assemblage types and sedimentary parameters often are temporally and spatially variable.

Motile populations, including non-migratory foragers, would be less stressed by sediment removal than infauna or sessile epifauna. Most macroepifaunal and demersal fish populations would have a low probability of being adversely impacted directly by the dredging of surficial sediments. Slow-moving or burrowing sessile epifauna inhabiting the project area include echinoderm and decapod taxa, and local populations of these types of benthic organisms would most likely experience a reduction in density due to sediment removal. Motile epifauna generally are migratory and are not endemic to the borrow sites. Most demersal populations exhibit naturally dynamic distributions, moving between areas within the Middle Atlantic Bight on a seasonal basis (MMS, 1989).

Any impacts of sediment removal on epifaunal and demersal taxa likely would be indirect in nature, through habitat alteration. A reduction of infaunal biomass resulting from sediment removal could have an indirect effect upon the distribution of certain demersal fishes and other epibenthic predators by interrupting established energy pathways to the higher trophic levels represented by these foraging taxa. Reductions in densities of the preferred prey of bottom-feeding taxa could induce migration of foragers to unimpacted areas. However, a relatively small percentage of infaunal prey items that typically are consumed by demersal taxa would be rendered unavailable for consumption as a result of prey removal along with sediments. Benthic predators simply would select alternative areas in which to forage. Because excavated areas are expected to recover relatively rapidly after dredging, loss of infaunal biomass due to sediment excavation is unlikely to adversely affect normal energy flow through North Carolina inner shelf sand bottoms.

In addition to widely documented spatial variation, the location and extent of some inner shelf-inhabiting infaunal and demersal populations vary seasonally in the study region. Seasonal variability should be considered when evaluating potential impacts from sand removal. The timing of sand removal would seem to be less critical for minimizing the impact upon infauna than for other faunal categories of concern (e.g., key pelagic species), due to the great abundance and reproductive potential of infaunal populations. Many numerically dominant infaunal taxa inhabiting the study region are known to exhibit either year-round or late winter-early spring periods of recruitment. Because of these patterns of recruitment and lower winter densities, removal of sand between late fall and early spring would result in less stress on benthic populations.

Sediment Suspension/Dispersion

Whether cutterhead suction dredging or hopper dredging ultimately is utilized for sand mining, the amount of sediment suspension that results from these excavation methods is not anticipated to be of a scale that would cause significant negative impacts to the benthic community. North Carolina sand resource areas are characterized by a relatively limited amount of very fine sediments, indicating that the area encompassing those resource areas currently is not a depositional environment, but is hydrologically dynamic. In general, benthic assemblages of the inner North Carolina shelf probably are adapted to periodic reworking of surficial sediments caused by tropical and extra-tropical storms. Impacts of dredging-induced elevations in turbidity (associated mainly with hopper dredging) would be short-term and localized. Motile taxa could avoid turbid areas, and are unlikely to be affected by sediment resuspension.

Sediment Deposition

Of the various faunal categories, infaunal and sessile epifaunal populations would be most negatively affected by significant deposition of sediments; however, efficient methods of sediment excavation would preclude all but a relatively minor amount of sediment deposition. Suspension and transport of sediments away from dredging sites should be minimal and any subsequent deposition will be insignificant in degree. In the unlikely event that significant dredging-related deposition of fine-grained sediments were to occur, the deposited sediments likely would not persist on the seafloor because of the high-energy inner shelf environment. However, some low or depressional areas of the seafloor could exhibit a substantial deposition of fine sediments under this scenario. Given the relatively small amount of sediment suspension anticipated to occur during dredging, the degree of burial should be substantially less than would be required to impact negatively on infaunal populations.

7.5.3.2 Potential Recolonization Rate and Success

The rate and nature of post-dredging recovery of benthic assemblages within an excavated borrow site will depend primarily on the depth of sand excavation. While surface area of impact could be minimized by excavating a shoal to a greater depth, deep excavation likely would require a greater length of time for complete recovery of infaunal assemblages within the impacted area. The creation of a bathymetrically abrupt pit has potential to inhibit water current flow through such a feature, possibly resulting in a “dead zone” characterized by deposition of fine particles and hypoxia or anoxia. This scenario would extend the duration of ecological impact beyond that which would occur with a more shallow cut over a much larger area.

Recent results of long-term environmental monitoring of a borrow site located 3.6 km offshore Coney Island have demonstrated potential consequences of dredging an abrupt pit feature (Barry A. Vittor & Associates, Inc., 1999). A nearby reference area also was sampled before (1992) and after dredging (1995 through 1998). Prior to dredging, average water depths were approximately 3 to 4 m at the Coney Island borrow site and in the reference area. After the last dredging in 1995, and up until the last monitoring event (1998), depths of borrow site stations varied from 6 to 15 m, while the average depth of reference area stations did not change during the study period. Prior to dredging, sediments at the borrow site were 55% medium to coarse sands, but by 1995 were fine to medium sands (<20% medium to coarse sand). By 1998, the silt/clay fraction (>20%) of borrow site sediments was significantly greater than in reference area sediments (4%). During each year following the last dredging event, infaunal assemblage composition at the borrow site was numerically dominated by deposit-feeding polychaetes (*Spio setosa* and *Streblospio benedicti*) and mollusks (primarily *Tellina agilis*); none of these species were ever observed in the reference area. Although hypoxic conditions have not been detected at the Coney Island borrow site, bathymetric alteration and subsequent deposition of fine sediments resulted in persistent alteration of natural assemblage composition.

While the initial impact on benthic assemblages would increase with a greater surface area of sand removal, the persistence of ecological impact that would occur with a relatively shallow excavation would be less than that of a deep pit. A maximum shoal excavation of 2 m (Areas 3 east and 4) or 3 m (Areas 1, 2, and 3 west) will result in little long-term impact because a more smoothly-graded, trough-like feature would allow greater bottom current flow. North Carolina sand resource areas exhibit natural inter-ridge trough features. These bathymetric depressions can be depositional areas for fine sediments and often support benthic assemblages that are different from nearby assemblages inhabiting gravel and sand. Ultimately, though, it is expected that only the leading edge of each shoal will be dredged and that depth of dredging will not substantially exceed the level of the ambient shelf surface.

The length of time required for reestablishment of pre-dredging infaunal assemblages within excavated sites partly depends on the length of time required for refilling of those mined areas. The relatively shallow water benthic habitats of the North Carolina inner shelf are strongly influenced by factors such as tidal currents and circulation, and storms. These same forces would tend to modify impacted sites in the direction of pre-dredging conditions. The rate of reestablishment of natural benthic conditions at dredged sites may depend especially on the extent of storm-induced sediment transport, which can be substantial at relatively shallow depths such as those in the region of the sand resource areas.

Assuming that the depth of sand excavation will not be so great as to substantially alter local hydrological characteristics, removal of benthic organisms along with sediments would be quickly followed by initial recolonization of the dredged sites by opportunistic infaunal taxa. Early-stage succession will begin within days of sediment removal, through settlement of larval recruits, primarily annelids and bivalves. Initial larval recruits likely would be dominated by populations of deposit feeding, opportunistic taxa, especially polychaetes and bivalves such as *Solemya velum* and *Tellina agilis*. These species are well adapted to environmental stress and exploit suitable habitat when it becomes available. Later successional stages of benthic recolonization will be more gradual, and involve taxa that generally are less opportunistic and longer lived. Immigration of motile annelids, crustaceans, and echinoderms into impacted areas also will begin soon after excavation.

The length of time required to reestablish infaunal assemblages also depends in large measure on the sediments exposed by dredging. Shoal sediments consist of well-sorted sands and also appear to be vertically uniform in composition. Sediments exposed by dredging probably will not differ substantially from existing surficial sediments In addition, the resource areas are characterized by a limited amount of fine sediments, indicating that they are not depositional in nature. Later stages of recolonization in dredged sites likely will occur in a timely manner and without persistent inhabitation by initial transitional assemblages, not unlike the process which has been documented elsewhere in the Middle Atlantic Bight (Kropp, 1995; Scott and Kelly, 1998).

Because the sedimentary regime of North Carolina sand resource areas is vertically uniform, recolonization of surficial sediments by later successional stages likely will proceed even if dredged shoals are not completely reestablished. Furthermore, dredging of only a small portion of the area within each of the resource areas will ensure that a supply of non-transitional, motile taxa will be available for rapid migration into dredged sites. While community composition may differ for a period of time after the last dredging, the infaunal assemblage type that exists in mined areas will be similar to naturally occurring assemblages in the study area, particularly those assemblages inhabiting inter-ridge troughs. Based on previous observations of infaunal reestablishment in dredged sites, the infaunal community in dredged sites most likely will become reestablished within 2 years, and will exhibit levels of infaunal abundance, diversity, and composition comparable to nearby non-dredged sites.

7.6 PELAGIC ENVIRONMENT

This section discusses the potential effects of hydraulic (cutterhead and hopper) dredging on water column organisms at a borrow site, and seasonal windows that would reduce the effects to particular species or groups. Groups of organisms considered include zooplankton (including eggs and larvae of economically important fish and shellfish species), squids, pelagic fishes, sea turtles, and marine mammals.

7.6.1 Zooplankton

7.6.1.1 Entrainment

Zooplankters encountering the suction field of hydraulic dredges will be easily drawn into the system (i.e., entrained). Entrained zooplankters are assumed to die from abrasion and physical trauma (LaSalle et al., 1991; Reine and Clarke, 1998). The most detrimental consequence of zooplankton entrainment is the death of fish and invertebrate larvae, which ultimately influences the age structure of adult populations.

The rate of zooplankton entrainment by hydraulic dredges depends upon local hydrographic patterns responsible for their transport and the spatial and temporal dynamics of local populations. Hydrographic patterns can be measured, whereas inherently variable zooplankton populations are more difficult to characterize (Sullivan and Hancock, 1977). Because of difficulties in measuring population parameters from field-collected data, direct estimates of zooplankton entrainment (and subsequent population effects) are not available in the dredging literature. An alternative to using field-collected data has been to develop numerical models that predict population effects given specific scenarios (discussed in LaSalle et al., 1991 and Reine and Clarke, 1998). Unfortunately, population effects estimated from models can differ greatly depending upon model assumptions (LaSalle et al., 1991; Reine and Clarke, 1998).

Entrainment rate also depends upon physical aspects of the dredging operation. Because the suction field of hydraulic dredges remains near the seafloor, species most susceptible to entrainment are those occurring in the lower portion of the water column. Taxa or life stages that spend part of their time associated with the benthic environment, such as demersal fish eggs or demersal zooplankton (Hammer and Zimmerman, 1979), would be especially vulnerable. Unfortunately, no information exists on the abundance or composition of demersal zooplankton in the sand resource areas. Several fish species in the region lay demersal eggs. Considering the high reproductive capacity of zooplankton along with the relatively small area of the dredge suction field and the volume of water entrained compared to the overall volume of surrounding waters, it is unlikely that entrainment would greatly affect zooplankton populations or assemblages in the North Carolina sand resource areas.

7.6.1.2 Turbidity

Sediments suspended and dispersed by the action of a working dredge can affect zooplankters by 1) interfering with feeding activity; 2) direct mortality and toxicity; and 3) physiological impairment.

Most crustacean zooplankters are filter feeders capable of filtering and processing particles between 3 and 10 m (Nival and Nival, 1976). Inorganic particles in this size range can easily foul the fine structures (setules) on feeding appendages of crustaceans such as copepods, and crab and shrimp larvae (Sullivan and Hancock, 1977). Laboratory studies have shown that mechanical disruption of feeding can affect growth and reproductive success (Kirk, 1992). Plankters feeding by ciliary action (e.g., echinoderm larvae) also would be susceptible to mechanical effects of suspended particles (Sullivan and Hancock, 1977).

Larval fishes are visual feeders that depend on adequate light levels for their foraging success (Blaxter, 1968). High turbidity reduces light levels in the water column, which in turn shortens the reactive distance between a larval fish and its prey. Laboratory studies have demonstrated the negative influence of elevated turbidity on prey capture rates for larvae of the herring *Clupea harengus harengus* (Johnston and Wildish, 1982), striped bass, *Morone saxatilis* (Morgan et al., 1983; Breitburg, 1988), and dolphin, *Coryphaena hippurus* (Jokiel, 1989). In one laboratory study, however, increased turbidity actually enhanced feeding abilities of larval herring *Clupea harengus pallisi* (Boehlert and Morgan, 1985). The authors suggested that suspended sediment may have provided better contrast against which small particles were viewed.

Direct mortality and toxicity caused by elevated turbidity varies with species and the nature of the sediment and sediment-bound contaminants. Crustacean zooplankters will ingest suspended inorganic particles that may or may not contain contaminants. Contamination is expected to be low in all sand resource areas. A laboratory study showed that copepods ingesting high amounts of “red mud” grew slower than control groups feeding only on diatoms (Paffenhofer, 1972). This was attributed to the non-nutritive value of the red mud rather than to any associated toxic compounds. Sediment-bound toxic compounds introduced into the water column may be ingested by zooplankters. These substances can be detrimental to zooplankters. However, studies with copepods exposed to deep sea mine tailings containing trace metals showed minimal effects (Hirota, 1981; Hu, 1981).

High turbidity can cause physiological changes that can kill or retard developing eggs and larvae of fishes and invertebrates (Davis and Hidu, 1969; Rosenthal, 1971). High concentrations of suspended sediment can kill or deform fish eggs (Rosenthal, 1971). Laboratory studies investigating effects of elevated turbidity on eggs and larvae of bivalves show that slight increases in turbidity actually stimulated larval growth, whereas large increases in turbidity caused abnormalities (Loosanoff, 1962; Davis and Hidu, 1969). Hatching success of fish eggs exposed to high suspended concentrations varies, but most studies show minimal effects from acute exposures in the 50 to 500 mg/L range (Auld and Schubel, 1978; Morgan et al., 1983; Jokiel, 1989). In these same studies, artificially high suspended sediment concentrations (1,000 to 8,000 mg/L) were required to induce mortality.

As with entrainment, the effects of suspended sediments on zooplankters is primarily restricted to the lower portion of the water column for a cutterhead dredge because the turbidity plume remains near the cutterhead with little of the plume reaching surface waters (LaSalle et al., 1991). Suspended sediment plumes in near-bottom waters may extend for up to several hundred meters laterally from the cutterhead. In contrast, hopper barges may create turbid surface plumes due to overwash (LaSalle et al., 1991). With either dredge type, the turbidity plume is expected to cover a small portion of the water column relative to the surrounding waters. Due to the limited areal extent and transient nature of the sediment plume, it is unlikely that turbidity would greatly affect zooplankton populations or assemblages in the North Carolina sand resource areas.

7.6.1.3 Project Scheduling

For open ocean environments, Sullivan and Hancock (1977) generalized that dredging effects on zooplankton would be minimal due to high spatial and temporal variability of the populations, whereas significant effects would be expected in enclosed waters with endemic populations. However, accurate prediction of the local effects of entrainment or dredge-produced turbidity on zooplankton populations of the sand resource areas requires adequate site-specific data. Zooplankton populations in general should not be subject to impacts from dredging, but available regional information (see Section 2.3.2.1) indicates that planktonic larvae, particularly those of fishes, occur in the project area especially during summer and fall months (Able and Fahay, 1998; Grothues and Cowen, 1999). Because adults of these species spawn offshore and larval and juvenile forms make their way back to inshore nursery areas such as Pamlico Sound through Oregon Inlet (e.g., Warlen and Burke, 1990) Sand Resource Area 3 could be construed as lying near an important recruitment corridor. The other sand resource sites are not within such an important position relative to coastal inlets and therefore should not require any special project scheduling consideration.

When data are inadequate to accurately predict the magnitude of dredging effects, environmental windows have been required to provide a conservative approach and lessen potential effects on key species. However, LaSalle et al. (1991) and Reine et al. (1998) have stressed the need to base future environmental windows on sound evidence, and have argued against subjectively selected environmental windows. Environmental windows delay projects and greatly increase costs (Dickerson et al., 1998), and their use should not be driven by subjective or overly conservative approaches. If Area 3 is used as a borrow site, an environmental window excluding summer and fall months could be considered to avoid dredging when fish juveniles and larvae are most prevalent, but only if additional data become available to determine the extent of impacts and justify the restriction. Progress toward understanding the real need for environmental windows can only be achieved by reducing the degree of uncertainty surrounding impacts and the means to avoid them (Dickerson et al., 1998).

7.6.2 Squids

7.6.2.1 Entrainment

No information exists regarding impacts of hydraulic dredging on squids. Nevertheless, squids could be entrained if they encountered the suction field of a hydraulic dredge. Some general aspects of squid behavior increase the chance of encountering the bottom-oriented dredge suction field. Adult squids are generally demersal by day and enter the water column at night to feed on zooplankton (Fischer, 1978). In addition, squids lay their eggs in large clusters on the seafloor (Vecchione, 1981).

7.6.2.2 Attraction

Because some squid species are attracted to lights at night (Fischer, 1978), it is likely that squids could be attracted to lights of a working dredge. This could draw them into the suction field and increase the chance of entrainment.

7.6.2.3 Project Scheduling

With no information on local squid populations available, reasonable predictions of demographic effects are difficult to make. As with the other pelagic organisms, dredging is unlikely to significantly impact squid populations in the vicinity of the sand resource sites. This precludes the need for an environmental window or specific project scheduling to protect squid resources.

7.6.3 Fishes

7.6.3.1 Entrainment

Entrainment of adult fishes by hydraulic dredging has been reported for several projects (Larson and Moehl, 1988; McGraw and Armstrong, 1988; Reine and Clarke, 1998). The most comprehensive study of fish entrainment took place in Grays Harbor, Washington during a 10-year period when 27 fish taxa were entrained (McGraw and Armstrong, 1988). Most entrained fishes were demersal species such as flatfishes, sand lance, and sculpin; however, three pelagic species (anchovy, herring, and smelt) were recorded. Entrainment rates for the pelagic species were very low, ranging from 1 to 18 fishes/1,000 cy (McGraw and Armstrong, 1988). Comparisons between relative numbers of entrained fishes with numbers captured by trawling showed that some pelagic species were avoiding the dredge. Another entrainment study conducted near the mouth of the Columbia River, Washington reported 14 fish taxa entrained at an average rate of 0.008 to 0.341 fishes/cy (Larson and Moehl, 1988). Few of the coastal pelagic fishes occurring offshore North Carolina should become entrained because the dredge's suction field exists near the bottom and many pelagic species have sufficient mobility to avoid the suction field.

7.6.3.2 Attraction

Even though dredges are temporary structures, they still can attract roving pelagic species. This may temporarily disrupt a migratory route for some members of the stock, but it is unlikely that there would be an appreciable negative effect.

7.6.3.3 Turbidity

Turbidity can cause feeding impairment, avoidance and attraction movements, and physiological changes in adult pelagic fishes. As discussed for larval fishes, pelagic species are primarily visual feeders. When turbidity reduces light penetration, the fishes' reactive distance decreases (Vinyard and O' Brien, 1976). Light scattering caused by suspended sediments also can affect a visual predator's ability to perceive and capture prey (Benfield and Minello, 1996).

Some species will actively avoid or be attracted to turbid water. Experiments with pelagic kawakawa (*Euthynnus affinis*) and yellowfin tuna (*Thunnus albacares*) demonstrated that these species would actively avoid experimental turbidity clouds, but also would swim directly through them during some trials (Barry, 1978). Turbidity plumes emanating from coastal rivers may retard or affect movements of some pelagic species.

Gill cavities can be clogged by suspended sediment, preventing normal respiration and mechanically affecting food gathering in planktivorous species (Bruton, 1985). High suspended sediment levels generated by storms have contributed to the death of nearshore and offshore fishes by clogging gill cavities and eroding gill lamellae (Robins, 1957).

The limited spatial and temporal extents of turbidity plumes from either cutterhead or hopper dredges are expected to be limited. Therefore, there should be no significant impact on adult pelagic fishes.

7.6.3.4 Project Scheduling

Hydraulic dredging should not present a significant problem for pelagic fishes offshore North Carolina. If an environmental window is sought to protect pelagic fishes from dredging impacts, the spring to fall period would encompass the peak seasons for the economically important species. Temporal scheduling as a means to avoid impacts is practical if the organism in question is highly concentrated in waters of the area during some specific time period. Quantitative data are lacking to support the use of an environmental window to lessen effects on pelagic fishes.

7.6.3.5 Essential Fish Habitat

The Magnuson-Stevens Fishery Conservation and Management Act (16 U.S.C. § 1801-1882) established regional Fishery Management Councils and mandated that Fishery Management Plans (FMPs) be developed to responsibly manage exploited fish and invertebrate species in Federal waters of the U.S. When Congress reauthorized this act in 1996 as the Sustainable Fisheries Act, several reforms and changes were made. One change was to charge the NMFS with designating and conserving Essential Fish Habitat (EFH) for species managed under existing FMPs. This was intended to minimize, to the extent practicable, any adverse effects on habitat caused by fishing or non-fishing activities, and to identify other actions to encourage the conservation and enhancement of such habitat.

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 interim final rule summarizing EFH regulations (62 FR 66531-66559) outlines additional interpretation of the EFH definition. Waters, as defined previously, include "aquatic areas and their associated physical, chemical, and biological properties that are used by fish, and may include aquatic areas historically used by fish where appropriate." Substrate includes "sediment, hard bottom, structures underlying the waters, and associated biological communities." Necessary is defined as "the habitat required to support a sustainable fishery and the managed species' contribution to a healthy ecosystem." "Fish" includes "finfish, mollusks, crustaceans, and all other forms of marine animal and plant life other than marine mammals and birds," whereas "spawning, breeding, feeding or growth to maturity" cover the complete life cycle of those species of interest.

The sand resource areas are within the region managed by the Mid-Atlantic Fishery Management Council (MAFMC); however, species included in FMPs by the South Atlantic Fishery Management Council (SAFMC) and Highly Migratory Species (HMS) Section of the Office of Sustainable Fisheries may occur in this region. Many species managed by these Federal groups also are under the purview of the Atlantic States Marine Fisheries Commission. The MAFMC produced several FMPs for single and mixed groups of species. All of these FMPs were recently amended to address EFH, including those for Atlantic surfclam and ocean quahog (MAFMC, 1998a); Atlantic mackerel, squids, and butterfish (MAFMC, 1998b); summer flounder, scup, and black sea bass (MAFMC, 1998c); bluefish (MAFMC, 1998d); and spiny dogfish (MAFMC, 1999). Amendments identified and described EFH for all life stages of managed species. In addition to the FMPs prepared by the MAFMC, the SAFMC prepared a single amendment (SAFMC, 1998) to cover a suite of managed species including shrimps, snapper-grouper, coastal pelagics, and red drum. Highly migratory species (tunas, sharks, and swordfish) are managed by the NMFS (NMFS, 1999). EFH for several species (and life stages) covered in these FMPs overlapped the four sand resource areas offshore North Carolina. EFH characteristics for these species are presented in Table 7-1.

Another EFH process component is designating Habitat Areas of Particular Concern (HAPCs). HAPCs are narrowly focused habitats with demonstrated direct habitat value for managed species. Several HAPCs are located in North Carolina marine waters and include sandy shoals off Cape Hatteras, Cape Fear, and Cape Lookout; Big Rock; Bogue Sound; New River; The Point; and Ten Fathom Ledge. None of these HAPCs encompasses the sand resource areas; therefore, direct effects from dredging would not be expected. General marine HAPCs that overlap or are in the vicinity of the sand resource areas include artificial reefs, *Sargassum*, water column, and hard/live bottom areas that could be affected by dredging.

Hard bottom is known to occur off northern North Carolina near the sand resource areas (Southeast Area Monitoring and Assessment Program—South Atlantic, 2001), and potential hard bottom also has been reported (Boss et al., 1999; Boss and Hoffman, 2001). Sand mining, dredge disposal, and anchoring are potential threats to hard/live bottom off North Carolina (Moser et al., 1995). Although no indication of hard/live bottom was found during the limited biological surveys that focused on soft bottom in the sand resource areas, more extensive surveys should be conducted in the future prior to dredging in and near specific borrow sites to determine if hard/live bottom is present and if protective measures are necessary. Determination of hard/live bottom survey requirements should consider the following three statements from Boss et al. (1999). Due to the low-relief and high-energy dynamics of this shelf environment, it is probable that these hard bottom areas are transient features of the seafloor. Major storms may redistribute sediment on the shelf such that some hard bottom areas will become covered, whereas new hard bottom areas will be exhumed. When exposed, these new hard bottom sites can be important benthic habitats because they present new space on which benthos may become established; however, when covered with even a thin layer (i.e., few cm) of loose sediment, they become non-productive (Renaud et al., 1996a,b). Based on these statements, if detailed hard/live bottom studies are deemed necessary in and near the sand resource areas in the future, it would be advisable to conduct the surveys immediately prior to dredging a particular borrow site due to the "probable" ephemeral nature of hard bottom in the region.

Although sand shoals are subject to currents, waves, and tidal forces, they are considered relatively permanent seafloor features. Most shoals were formed during Pleistocene low sea level periods when the continental shelf was exposed. Shoals could be continually altered or completed removed as a result of dredging projects and are unlikely to reform as they were

Table 7-1. Invertebrate and fish species for which Essential Fish Habitat (EFH) has been identified in the vicinity of the four sand resource areas offshore North Carolina. Species are listed in phylogenetic order.

Species	Life Stage	EFH Document
Invertebrates		
Ocean quahog (*Arctica islandica*)	Adults, juveniles	MAFMC, 1998a
Atlantic surfclam (*Spisula solidissima*)	Adults, juveniles	MAFMC, 1998a
Long-finned squid (*Loligo pealei*)	Adults, juveniles	MAFMC, 1998b
Short-finned squid (*Illex illecebrosus*)	Adults, juveniles	MAFMC, 1998b
Fishes		
Spiny dogfish (*Squalus acanthias*)	Adults, juveniles	MAFMC, 1999
Dusky shark (*Carcharhinus obscurus*)	Late juveniles/subadults, neonates/early juveniles	NMFS, 1999
Sandbar shark (*Carcharhinus plumbeus*)	Adults, late juveniles/subadults, neonates/early juveniles,	NMFS, 1999
Tiger shark (*Gaelocerdo cuvieri*)	Adults, late juveniles/subadults, neonates/early juveniles	NMFS, 1999
Sand tiger shark (*Carcharius taurus*)	Adults, neonates/early juveniles	NMFS, 1999
Atlantic sharpnose shark (*Rhizoprionodon terraenovae*)	Adults	NMFS, 1999
Atlantic sturgeon (*Acipenser oxyrhynchus*)	Adults, juveniles	ASMFC, 1998
Atlantic herring (*Clupea harengus*)	Adults	ASMFC, 1999
Red hake (*Urophycis chuss*)	Juveniles, larvae, eggs	NEFMC, 1998
Monkfish (*Lophius americanus*)	Larvae, eggs	NEFMC, 1998
Black sea bass (*Centropristis striata*)	Adults, juveniles, larvae	MAFMC, 1998c
Bluefish (*Pomatomus saltatrix*)	Adults, juveniles, larvae, eggs	MAFMC, 1998d
Cobia (*Rachycentron canadum*)	Adults	SAFMC, 1998
Scup (*Stenotomus chrysops*)	Adults, juveniles	MAFMC, 1998c
Red drum (*Sciaenops ocellatus*)	Adults	SAFMC, 1998
King mackerel (*Scomberomorus cavalla*)	Adults	SAFMC, 1998
Spanish mackerel (*Scomberomorus maculatus*)	Adults	SAFMC, 1998
Atlantic mackerel (*Scomber scombrus*)	Adults, juveniles, larvae, eggs	MAFMC, 1998b
Butterfish (*Peprilus triacanthus*)	Adults, juveniles, larvae, eggs	MAFMC, 1998b
Windowpane flounder (*Scophthalmus aquosus*)	Juveniles	NEFMC, 1998
Summer flounder (*Paralichthys dentatus*)	Adults, juveniles, larvae, eggs	MAFMC, 1998c

ASMFC = Atlantic States Marine Fisheries Commission.
MAFMC = Mid-Atlantic Fishery Management Council.
NEFMC = New England Fishery Management Council.
NMFS = National Marine Fisheries Service.
SAFMC = South Atlantic Fishery Management Council.

originally if changes are drastic. The extent to which partial or complete shoal removal affects fish populations is uncertain. Some have speculated that fishes use shoals for feeding, staging, or orientation areas during short-term or long-term migrations. Although no specific scientific information exists supporting these assertions, the potential for impacts cannot be discounted (Research Planning, Inc. et al., 2001).

The area encompassed by the four sand resource areas is very small relative to the mapped EFH characteristics. For this reason, the effect of dredging on EFH for the managed species is expected to be minimal.

7.6.4 Sea Turtles

7.6.4.1 Entrainment

The main potential effect of dredging on sea turtles is physical injury or death caused by entrainment. Numerous sea turtle injuries and mortalities have been documented during dredging projects along Florida's east coast (Studt, 1987; Dickerson et al., 1992; Slay, 1995). Several turtles have been taken during dredging operations in the Mid-Atlantic states in recent years (NMFS, 1996). However, dredging has not been implicated as a major cause of death or injury to sea turtles in the region (NMFS, 1996).

Of the five turtle species that may occur off North Carolina, three (loggerhead, Kemp's ridley, and green) are considered to be at risk from dredging activities because of their benthic feeding habits (Dickerson et al., 1992). Loggerheads are the most abundant turtles in the project area, and historically, they have been the species most frequently entrained during hopper dredging, possibly accounting for up to 86% of the total (Reine and Clarke, 1998). Kemp's ridley and green turtles historically have accounted for much smaller portions of the total. Leatherbacks, which also occur in North Carolina waters, are unlikely to be affected by dredging because they feed in the water column rather than on the bottom (NMFS, 1996). Hawksbills are unlikely to be affected because they are the least common turtles in the area and occur only as occasional vagrants.

Physical impact can occur when a turtle feeding or resting on the seafloor is contacted by the dredge head. Two types of dredges may be used on the proposed project. Cutterhead suction dredges are considered unlikely to kill or injure turtles, perhaps because the cutterhead encounters a smaller area of seafloor per unit time, allowing more opportunity for turtles to escape (Palermo, 1990). Hopper dredges are believed to pose the greatest risk to sea turtles (Dickerson, 1990; NMFS, 1997). There has been considerable research into designing modified hopper dredges with turtle deflectors that reduce the likelihood of entraining sea turtles (Studt, 1987; Berry, 1990; Dickerson et al., 1992; Banks and Alexander, 1994; USACE, 1999). If a hopper dredge is used on this project during the loggerhead turtle nesting season of April through September, the NMFS may require turtle monitoring and use of a turtle-deflecting draghead.

Chelonid sea turtles (i.e., those other than leatherbacks) feed primarily in depths of 15 m or less (NMFS, 1996). The risk of physical impacts to turtles would appear to be greatest in the shallowest water depths in each potential borrow site. However, there is also risk in deeper water because when turtles feed there, they tend to stay on the bottom longer (NMFS, 1996).

7.6.4.2 Habitat Modification

Juvenile and subadult loggerheads, Kemp's ridleys, and greens use northeastern coastal waters as developmental habitat, foraging on benthic organisms (see Section 2.3.2.4).

Therefore, when borrow sites have significant concentrations of benthic resources, dredging can reduce food availability both by removing potential food items and altering the benthic habitat (NMFS, 1996). Effects would be temporary, as benthic populations would be expected to recover over a period of months to years (see Section 7.5.3). In addition, borrow sites represent only a small portion of the shallow benthic habitat available off North Carolina. Trawl sampling in support of this document showed that potential food for turtles (e.g., various benthic crustaceans, mollusks, and echinoderms) was present in the borrow sites (see Section 6.0).

7.6.4.3 Turbidity and Anoxia

Sea turtles in and near the project area may encounter turbid water that could temporarily interfere with feeding. However, due to the limited aerial extent and transient occurrence of the sediment plume, turbidity is considered unlikely to significantly affect turtle behavior or survival.

Measurements around cutterhead dredging operations show that elevated levels of suspended sediments are restricted to the immediate vicinity of the cutterhead with little turbidity reaching surface waters (LaSalle et al., 1991). Maximum suspended sediment concentrations typically occur within 3 m above the cutterhead and decline exponentially to the sea surface. Suspended sediment concentrations in near-bottom waters may be elevated up to several hundred meters laterally from the cutterhead location.

Hopper dredging operations also produce turbidity as the dragheads are pulled through bottom sediments. However, the main source of turbidity during hopper dredging operations is sediment release during hopper overflow (LaSalle et al., 1991). A plume may occasionally be visible at distances of 1,200 m or more.

In addition to turbidity, dredging may produce localized hypoxia/anoxia in the water column due to oxygen consumption of the suspended sediments (LaSalle et al., 1991). In general, oxygen levels in the plume and near-bottom waters may approach zero, but levels in adjacent waters outside the plume are at or near normal. Due to the limited extent and transient occurrence of hypoxia/anoxia, no significant effects on turtles are expected.

7.6.4.4 Noise

Dredging is one of many human activities in the marine environment that produce underwater noise. Sea turtles have limited hearing ability (Ridgway et al., 1969; Lenhardt, 1994), and its role in their life cycle and behavior is poorly known. It is believed that sea turtles do not rely on sound to any significant degree for communication or food location, although it has been suggested that low-frequency sound may be involved in natal beach homing behavior (Dodd, 1988). The latter could be a consideration during the nesting season.

There are indications that underwater noise is unlikely to significantly affect turtles. First, studies in the Gulf of Mexico have shown some evidence for positive association of sea turtles with petroleum platforms (Rosman et al., 1987; Lohoefener et al., 1990) despite the industrial noise associated with these sites. Second, experiments testing the use of seismic airguns to repel turtles from dredging activities indicate that even loud noises cause avoidance only at very close range (e.g., 100 m or less) (Moein et al., 1994; Zawila, 1994). If noise does have any impact on turtles, it would most likely be positive by encouraging avoidance of the dredge.

7.6.4.5 Project Scheduling Considerations

Project scheduling is one way to avoid or minimize turtle impacts during dredging (Studt, 1987; Arnold, 1992). If a hopper dredge is used, then it would be best to avoid the loggerhead nesting and hatching season, which has been reported as May 1 through November 15 of any year (USFWS as cited in USACE, 2000). This same period would generally have higher risk of encountering juvenile and subadult Kemp's ridley and green turtles. However, the vagaries of winter weather off North Carolina may make it difficult to prohibit dredging during these months. If use of a hopper dredge during this season cannot be avoided, then other mitigation and monitoring requirements are likely to be imposed, such as turtle monitoring and use of a turtle-deflecting draghead (NMFS, 1996). If a cutterhead suction dredge is used, seasonal or other restrictions are considered unnecessary because there is little likelihood of killing or injuring sea turtles.

7.6.5 Marine Mammals

7.6.5.1 Physical Injury

Marine mammals are unlikely to be physically injured by dredging *per se* because they generally do not rest on the bottom and most can avoid contact with dredging vessels and equipment. The odontocete marine mammals most likely to be found in nearshore waters off North Carolina, such as bottlenose dolphin and Atlantic spotted dolphin, are agile swimmers that are presumed capable of avoiding physical injury during dredging.

However, physical injury from vessel strikes is a serious concern for three endangered species of mysticetes: North Atlantic right whale, fin whale, and humpback whale. Recovery plans for these species identify vessel strikes as a contributing factor impeding their recovery (NMFS, 1991a,b; Reeves et al., 1998). Vessel strikes are an especially serious concern for North Atlantic right whales. NMFS published regulations in February 1997 restricting vessel approaches of North Atlantic right whales. These regulations prohibit all approaches within 460 m of any North Atlantic right whale, whether by boat, aircraft, or other means (NMFS, 1998). Measures to minimize the potential for vessel strikes of endangered whales could be part of any Biological Opinion issued by the NMFS for dredging off North Carolina.

The harbor porpoise, which is a candidate for listing as a threatened species, is unlikely to be injured by dredging vessels or equipment. The major threat to the recovery of this species is gillnetting (NMFS, 1998). The NMFS has indicated that interactions of this species with dredging are unlikely (U.S. Environmental Protection Agency, 1997).

7.6.5.2 Turbidity

Marine mammals in and near the project area may encounter turbid water during dredging. This turbidity could temporarily interfere with feeding or other activities, but the animals could easily swim to avoid turbid areas. Due to the limited areal extent and transient occurrence of the sediment plume, turbidity is considered unlikely to significantly affect marine mammal behavior or survival.

7.6.5.3 Noise

Dredging can be a significant source of continuous underwater noise in nearshore areas, particularly in low frequencies (<1,000 Hz) (Richardson et al., 1995). This noise typically diminishes to background levels within about 20 to 25 km of the source (Richardson et al., 1995). Noise levels are not sufficient to cause hearing loss or other auditory damage to marine mammals (Richardson et al., 1995). However, some observations in the vicinity of dredging operations and other industrial activities have documented avoidance behavior, while in other cases, animals seem to develop a tolerance for the industrial noise (Malme et al., 1983; Richardson et al., 1995). Due to the frequency range of their hearing, mysticetes (baleen whales) are more likely to be affected by low-frequency noise than are odontocetes. The main concern would be that dredging noise could cause avoidance of the project area during humpback whale and (especially) North Atlantic right whale migrations.

7.6.5.4 Project Scheduling Considerations

Common shelf species such as bottlenose dolphin and Atlantic spotted dolphin may be present year-round and, as noted above, are unlikely to be adversely affected by dredging. Harbor porpoise occurrence is more seasonal (primarily spring and fall), but the likelihood of impact is so low that it does not warrant seasonal restrictions on dredging.

Fin whales would be most likely to occur during winter, whereas humpback and North Atlantic right whales could occur as transients during spring and fall. There is no “resident” population of these whales in the study region; rather, they would be temporary inhabitants, or would be transiting the area during seasonal migrations. Generally, the probability of encountering these species in the project area would be lowest during summer. The months of March and April would be least favorable because North Atlantic right whales are expected to migrate northward in shallow waters along the North Carolina coast during this period (Lee and Socci, 1989; MMS, 1990). Whether or not seasonal restrictions on dredging are implemented, measures to minimize possible vessel interactions with endangered whales are likely to be required by NMFS.

7.7 POTENTIAL CUMULATIVE EFFECTS

Cumulative physical environmental impacts from multiple sand extraction scenarios at one or all sand borrow sites within the study area were evaluated to assess long-term effects at potential borrow sites and along the coastline. Results presented above for wave and sediment transport processes reflect the impact of large extraction scenarios from one or multiple offshore sites that are expected to be within the cumulative sand resource needs of the State for the next 10 years. It was determined that no significant changes to longshore sediment transport will result from the modeled borrow site configurations, where borrow Sites 3 west and 3 east were modeled separately. If these sites were dredged simultaneously, the potential impacts were estimated to exceed the significance criterion and may require mitigation along the affected shoreline, or a redesign of the borrow site configuration. Overall, the cumulative impacts of sand mining offshore North Carolina on wave propagation and sediment transport processes are expected to be negligible under the conditions imposed.

Cumulative impacts resulting from multiple sand mining operations within a sand resource area are a concern when evaluating potential long-term effects on benthic and pelagic assemblages. The most likely mechanism that could result in adverse cumulative effects is the extraction of sand from the same shoal site more than once, resulting in a relatively deep pit feature where development of natural benthic assemblages is impeded. For the purpose of this analysis, it is assumed that a different area of the targeted sand shoal, or a different shoal, would be dredged each replenishment interval. Given that the expected beach replenishment interval is on the order of 5 to 10 years, and that the expected recovery time of the affected benthic community after sand removal is anticipated to be much less than that (within 2 years), the potential for significant cumulative benthic impacts is remote. No cumulative impacts to the pelagic environment, including zooplankton, squids, fishes, sea turtles, and marine mammals, are expected from multiple sand mining operations within a sand resource area.

8.0 CONCLUSIONS

The primary purpose of this study was to address environmental concerns associated with potential sand dredging from the OCS offshore Dare County, NC for beach replenishment. Primary concerns focused on physical and biological components of the environment at four proposed sand resource areas. Biological and physical processes data were analyzed to assess potential impacts of offshore dredging activities within the study area to minimize or preclude long-term adverse environmental impacts at potential borrow sites and along the coastline landward of these sites. Furthermore, wave transformation and sediment transport numerical modeling were used to simulate physical environmental effects of proposed sand dredging operations to ensure that offshore sand resources are developed in an environmentally responsible manner. Of the four potential sand resource areas, five borrow sites were chosen for evaluating sand extraction scenarios based on historical beach replenishment needs and resource information from the NCGS and MMS.

The following summary documents results and conclusions regarding potential environmental effects of sand mining on the OCS for replenishing sand to eroding beaches. Because benthic and pelagic biological characteristics are in part determined by spatially varying physical processes throughout the study area, physical processes analyses are summarized first.

8.1 WAVE TRANSFORMATION MODELING

Excavation of an offshore borrow site can alter incoming wave heights and the direction of wave propagation. Offshore topographic relief causes waves to refract toward the shallow edges of borrow sites. Changes in the wave field caused by borrow site geometry may change local sediment transport rates, where some areas may experience a reduction in longshore transport and other areas may show an increase. The most effective means of quantifying physical environmental effects of sand dredging from shoals on the continental shelf is by applying wave transformation numerical modeling tools that recognize the random nature of incident waves as they propagate onshore. To determine the potential physical impacts associated with dredging at borrow sites located offshore Dare County, NC, spectral wave transformation modeling (STWAVE) was performed for existing and post-dredging bathymetric conditions. Comparison of computations for existing and post-dredging conditions illustrated the relative impact of borrow site excavation on wave-induced coastal processes. Although the interpretation of wave modeling results is relatively straightforward, evaluating the significance of predicted changes for accepting or rejecting a borrow site is more complicated.

As part of any offshore sand mining effort, the MMS requires evaluation of potential environmental impacts associated with alterations to nearshore wave patterns. To determine potential impacts associated with borrow site excavation, the influence of borrow site geometry on local wave refraction patterns was evaluated. Because large natural spatial and temporal variability exists within the wave climate at a particular site, determination of physical impacts associated with sand mining must consider the influence of process variability. A method based on historical wave climate variability, as well as local wave climate changes directly attributable to borrow site excavation, was applied to determine appropriate criteria for assessing impact significance.

From existing conditions model results, bottom topography offshore Bodie Island modifies waves as they propagate shoreward. For example, the shoal in the vicinity of Borrow Site 1 refracts the wave field, causing a slight focusing of wave energy behind the feature. Wave heights behind the shoal are about 0.4 m greater than wave heights at the northern and southern limits of the shoal (see Figure 4-9). Because energy is conserved, focusing of wave energy behind the shoal causes a reduction of energy at the northern and southern margins of the shoal, which is apparent by the reduced wave heights in these areas.

In addition to the effects of offshore bottom features, waves were refracted by the straight and parallel bottom contours in the nearshore. As with changes in wave direction, wave heights also were modified by nearshore bathymetry. Waves begin to shoal (increase in height) about 500 m offshore, and increase in height by 0.2 m before breaking begins. Wave heights are reduced as energy dissipates in the surf zone, which is about 60 m wide for waves approaching from the southeast.

Output from post-dredging model runs indicate that wave heights within borrow sites are reduced relative to existing conditions, and this effect was more pronounced in cases that had greater wave heights. Wave fields landward of proposed borrow sites are modified by refraction. As waves propagate across a borrow site (deeper water than the surrounding area), wave refraction guides waves away from the center of the excavation site and toward the shallow edges. The net effect is to create a shadow zone of reduced wave energy immediately landward of a borrow site and a zone of increased wave energy updrift and downdrift of the borrow site. In the immediate vicinity of Site 2, for example, wave heights increased by a maximum of 0.05 m at the northern and southern edges of the borrow site and decreased by a maximum of 0.06 m behind the borrow site.

Because spectral wave model results were used, and because different frequencies in the spectrum were refracted to varying degrees at the borrow sites, regions of increased and reduced wave energy gradually diffuse as the wave field approaches shore. As such, borrow sites farther offshore affect a greater length of shoreline, however the actual magnitude of the impact was reduced because the affected wave field had a greater distance to diffuse (see Figure 4-11). This was evident from comparing the effect of Sites 1 and 2. Borrow Site 1 is the larger of the two, but farther offshore, and therefore the wave height change from existing to post-dredging conditions at the shoreline was less than changes caused by Site 2.

During storm conditions (Case 8), where wave period was significantly larger than normal wave characteristics, waves were more affected by offshore bathymetric gradients. Although the direction of wave propagation was not modified as much as was indicated under normal conditions, wave heights changed significantly (e.g., a maximum height of 2.4 m at the southern side of Oregon Inlet) relative to offshore conditions. At offshore shoals directly east of the inlet, wave heights increase approximately 0.7 m over the offshore boundary condition. Several shoal areas along the modeled coastline show similar impacts on wave heights.

The area of maximum increased wave heights for post-dredging conditions was located at the northernmost corner of Site 1, where wave heights increased 0.09 m over existing conditions. The area of maximum wave height decrease was located at the landward corner of Site 1, where wave heights were reduced by 0.12 m from existing conditions. Model output for storm wave conditions indicates that the length of affected shoreline where borrow site shadows propagate extends approximately 40 km to the north, starting from about 3 km north of Oregon Inlet. Overall, wave transformation affected by potential borrow site geometry was minimal during normal and storm conditions.

8.2 CIRCULATION AND SEDIMENT TRANSPORT DYNAMICS

Current measurements and analyses and wave transformation modeling provided baseline information on incident processes impacting coastal environments under existing conditions and with respect to proposed sand mining activities for beach replenishment.

Ultimately, the most important data set for understanding physical processes impacts from offshore sand extraction is changes in sediment transport dynamics resulting from potential sand extraction scenarios relative to existing conditions.

While no large-scale predictive circulation models were developed to quantify effects of dredging at sand borrow sites, the analysis of current patterns resulting from this study suggests proposed sand mining will have negligible impact on large-scale shelf circulation. The proposed sand mining locations are small relative to the entire shelf area, and it is anticipated that proposed dredging will not remove enough material to significantly alter major bathymetric features in the region. Therefore, the forces and geometric features that principally affect circulation patterns will remain relatively unchanged.

Three independent sediment transport analyses were completed to evaluate physical environmental impacts due to sand mining. First, historical sediment transport trends were quantified to document regional, long-term sediment movement throughout the study area using historical bathymetric data sets. Erosion and accretion patterns were documented, and sediment transport rates in the littoral zone and at offshore borrow sites were evaluated to assess potential changes due to offshore sand dredging activities. Second, sediment transport patterns at proposed offshore borrow sites were evaluated using wave modeling results and current measurements. Post-dredging wave model results were integrated with regional current measurements to estimate sediment transport trends for predicting borrow site infilling rates. Third, sediment transport was predicted using wave modeling output to estimate potential impacts to the longshore sand transport system (beach erosion and accretion). All three methods were compared for documenting consistency of measurements relative to predictions, and potential physical environmental impacts were identified.

8.2.1 Historical Sediment Transport Patterns

Regional geomorphic changes between 1862/70 to 1970/96 were analyzed for assessing long-term, net coastal sediment transport dynamics. Although these data did not provide information on potential impacts of sand dredging from proposed borrow sites, they did provide a means of verifying predictive sediment transport models relative to infilling rates at borrow sites and longshore sand transport.

Shoreline position and nearshore bathymetry change documented four important trends relative to study objectives. First, the predominant direction of sediment transport on the continental shelf and along southern Bodie Island was north to south. Second, the most dynamic features within the study area were the beaches and shoals associated with Oregon Inlet. Third, alternating bands of erosion and accretion on the continental shelf east of the Federal-State boundary illustrated relatively slow but steady reworking of the upper shelf surface as sand ridges migrated from north to south. The process by which this was occurring at all sand resource areas suggested that borrow sites in these regions would fill with sand transported from the adjacent seafloor at rates ranging from 20,000 to 70,000 m^3/yr. Fourth, net longshore transport rates determined from seafloor changes in the littoral zone between Kitty Hawk and Oregon Inlet indicated increasing transport rates north and south of a point about 10 km north of the inlet. Net longshore transport near Nags Head was about 160,000 m^3/yr to the north, increasing to about 335,000 m^3/yr near Kitty Hawk. These rates are very consistent with those determined from wave modeling and sediment transport predictions.

8.2.2 Sediment Transport at Potential Borrow Sites

In addition to predicted modifications to the wave field, potential sand mining at offshore borrow sites resulted in minor changes in sediment transport pathways in and around the dredged regions. Modifications to bathymetry caused by sand mining only influenced local hydrodynamic and sediment transport processes in the offshore area. Although wave heights changed at the dredged borrow sites, areas adjacent to the sites did not undergo dramatic changes in wave or sediment transport characteristics.

Initially, it is anticipated that sediment transport at borrow sites will occur rapidly after sand dredging is completed. For water depths at the proposed borrow sites, minimal impacts to waves and regional sediment transport are expected during infilling. The characteristics of sediment that replaces dredged material during infilling will vary based on location, time of dredging, and storm characteristics following dredging episodes. Average transport rates ranged from a minimum of about 38,000 m^3/yr (Sites 3 east and 4) to a high of about 123,000 m^3/yr (Site 2), while the infilling time varies between 37 to 98 years. Site 2 had the greatest infilling rate due to its shallow water depth relative to the other sites and its large perimeter. Because Site 2 is in shallow water, wave-induced currents and background currents were larger than at deeper surrounding sites, and more sediment was mobile in the proximity of the borrow site. Furthermore, sites that have a larger surface area generally will trap more sediment in a given time period. The range of infilling times was based of the volume of sand numerically dredged from a borrow site, as well as the sediment transport rate. Infilling times would have been reduced if storm events were incorporated in the analysis.

8.2.3 Nearshore Sediment Transport Modeling

Comparisons of average annual sediment transport potential were performed for existing and post-dredging conditions to indicate the relative impact of dredging to longshore sediment transport processes. Sediment transport potential is a useful indicator of shoreline impacts caused by offshore borrow sites because the computations include the borrow site influence on wave height and direction. Net and gross transport potential were computed using existing wave conditions and post-dredging conditions for two alternate borrow site configurations: 1) Sites 1, 2, 3 east, and 4 modeled together, and 2) Sites 1, 2, 3 west, and 4 modeled together. Analysis of gross and net transport potential indicated that there was a reversal of the direction of transport along southern Bodie Island. North of this spot, net transport was to the north, while south of this point to Oregon Inlet, net transport was strongly to the south. Computed north- and south-directed transport potential showed that transport was strongly bi-directional, with a gross transport magnitude of approximately 600,000 m^3/yr far north of Oregon Inlet and a net transport magnitude of only 250,000 m^3/yr. Closer to the inlet, littoral drift became more unidirectional and to the south, with gross and net transport potential magnitudes peaking at over 600,000 m^3/yr.

Difference in longshore transport potential between existing conditions and the two borrow site configurations resulted in a maximum negative change (post-dredging minus existing condition) in computed net sediment transport potential for the second configuration (Sites 1, 2, 3 west, and 4), where peak change was -34,000 m^3/yr, or 45% of the net transport potential at this point. The maximum positive change was approximately 14,000 m^3/yr or only 8% of the net transport potential computed at this point. The final determination of dredging significance was made by comparing actual change in transport potential between existing and post-dredging conditions to a significance envelope of one-half the standard deviation ($\pm 0.5\sigma$) along the shoreline (Kelley et al., 2001). It was determined that no significant changes to longshore sediment transport would result from the modeled borrow site configurations, where Sites 3 west and 3 east were modeled separately. For sites dredged simultaneously, the impacts were estimated to exceed the ±0.5σ, and therefore would require mitigation along the affected shoreline or a redesign of the borrow site configuration, likely a reduction in maximum design depth at one of the sites.

8.3 BENTHIC ENVIRONMENT

Results of field surveys for biological characterization agree well with previous descriptions concerning benthic assemblages associated with shallow shelf habitats offshore North Carolina. Benthic assemblages surveyed from the sand resource areas consisted of members of the major invertebrate and vertebrate groups commonly found in the general area. Numerically dominant infaunal groups included numerous crustaceans, echinoderms, mollusks, and polychaetes, while epifaunal taxa consisted primarily of decapods, sea stars, and squid. Canonical correlation analysis indicated that the composition of benthic assemblages inhabiting North Carolina sand resource area stations was affected primarily by survey, and secondarily by sediment type. Temporal variability in infaunal assemblage composition also was evidenced by both qualitative and quantitative community measures. Only 34% of the infaunal taxa sampled over the entire project was collected during both the May and September surveys. Most (59%) of the remainder of censused taxa were collected only during the September cruise, resulting in higher mean species richness values compared to the May survey. Also, infaunal abundance was greater during the September survey (2,967/m^2) than during May (994/m^2).

Biological surveys of the sand resource areas support the findings of numerous other investigations in the region that have found strong associations of infaunal taxa with particular sedimentary habitats. This infauna-habitat relationship was apparent in the results of the surveys, despite relatively limited sampling in the study region. Canonical correlation analysis indicated that, after survey, the composition of benthic assemblages inhabiting sand resource area stations mostly was affected by relative percentages of gravel and sand. Infaunal assemblage distributions reflected sediment type distributions. Apparent changes in surficial sediment composition between May and September probably accounted for some of the between-survey differences in infaunal assemblage composition.

Numerically dominant fishes collected during the 1998 sand resource area surveys are typical components of demersal assemblages in the study region. Fishes such as clearnose skate (*Raja eglanteria*), flounder (*Paralichthys* sp.), scup (*Stenotomus chrysops*), and searobin (*Prionotus scitulus*) were numerical dominants during the surveys and these species consistently are among the most ubiquitous and abundant demersal taxa in the region. Despite inherent spatial and temporal heterogeneity in the distribution and abundance of demersal fishes and low numbers in trawls, results of the 1998 surveys of the sand resource areas generally are consistent with results of historical demersal survey results in the region.

Potential benthic effects from dredging will result from sediment removal, suspension/dispersion, and deposition. Effects on infaunal populations will occur primarily through removal of individuals along with sediments. Effects are expected to be short-term and localized. Seasonality and recruitment patterns indicate that removal of sand between late fall and early spring would result in less stress on benthic populations. Early-stage succession will begin within days of sand removal, through larval recruitment dominated by opportunistic taxa, especially polychaetes and bivalves such as *Solemya velum* and *Tellina agilis*. These species are adapted to environmental stress and exploit suitable habitat when it becomes available. Later successional stages of benthic recolonization will be more gradual, involving taxa that generally are less opportunistic and longer lived. Immigration of motile annelids, crustaceans, and echinoderms into impacted areas also will begin soon after excavation.

While community composition may differ for a period of time after the last dredging, the infaunal assemblage type that exists in mined areas will be similar to naturally occurring assemblages in the study region, particularly those assemblages inhabiting inter-ridge troughs. Based on previous observations of infaunal reestablishment, and assuming that dredged sites do not create a sink for very fine sediments or result in hypoxic or anoxic conditions, the infaunal community in dredged sites most likely will become reestablished within 2 years, and will exhibit levels of infaunal abundance, diversity, and composition comparable to nearby non-dredged areas. Given that the expected beach replenishment interval is on the order of a decade, and that the expected recovery time of the affected benthic community after sand removal is anticipated to be much less than that, the potential for significant cumulative benthic impacts is remote.

8.4 PELAGIC ENVIRONMENT

Zooplankters could be affected by entrainment and turbidity. Considering the high reproductive capacity of zooplankton along with the relatively small area of the dredge suction field and the volume of water entrained compared to the overall volume of surrounding waters, it is unlikely that entrainment or turbidity would greatly affect zooplankton populations or assemblages in the North Carolina sand resource areas. If borrow sites are used in Area 3, an environmental window excluding summer and fall months could be considered to avoid dredging when fish juveniles and larvae are most prevalent, but only if additional data become available to determine the extent of impacts and justify the restriction.

Squids could be entrained if they encountered the suction field of a hydraulic dredge. In addition, squid eggs that are laid in large clusters on the seafloor could be removed with sediments. Dredging is unlikely to significantly impact squid populations in the vicinity of the sand resource areas. This precludes the need for an environmental window or specific project scheduling to protect squid resources.

Dredging should not present a significant problem for pelagic fishes offshore North Carolina. Potential effects to fishes could occur through entrainment, attraction, and turbidity. If an environmental window is sought to protect pelagic fishes from dredging impacts, the spring to fall period would encompass the peak seasons for the economically important species. Quantitative data are lacking to support the use of an environmental window to lessen effects on pelagic fishes.

EFH for several fish species (and life stages) overlap the four sand resource areas offshore North Carolina. The region encompassed by the four sand resource areas is very small relative to the mapped EFH characteristics. For this reason, the effect of dredging on EFH for the managed species is expected to be minimal.

The main potential effect of dredging on sea turtles is physical injury or death caused by the suction and/or cutting action of the dredge head. No significant effects on turtles are expected from turbidity, anoxia, or noise. Three sea turtle species that typically occur off North Carolina (loggerhead, Kemp's ridley, and green) are considered to be at risk because of their benthic feeding habits. Loggerheads are the most abundant turtles in the project area, and historically, they have been the species most frequently entrained during hopper dredging. If a hopper dredge is used, then it would be best to avoid the loggerhead nesting season from April through September. This same period would generally have higher risk of encountering juvenile and subadult Kemp’s ridley and green turtles. However, the vagaries of winter weather off North Carolina make it infeasible to prohibit dredging during these months. If use of a hopper dredge during this season cannot be avoided, then other mitigation and monitoring requirements may be appropriate, such as turtle monitoring and use of a turtle-deflecting draghead. If a cutterhead suction dredge is used, seasonal or other restrictions are considered unnecessary because there is little likelihood of killing or injuring sea turtles.

Marine mammal species occurring commonly on the shelf, such as bottlenose dolphin and Atlantic spotted dolphin, may be present year-round but are unlikely to be adversely affected by dredging due to their agility. Harbor porpoise occurrence is more seasonal (primarily spring and fall), but the likelihood of impact is so low that it does not warrant seasonal restrictions on dredging. Fin whales would be most likely to occur during winter, whereas humpback and North Atlantic right whales could occur as transients during spring and fall. There is no "resident" population of these whales in the study region; rather, they would be temporary inhabitants, or would be transiting the area during seasonal migrations. Generally, the probability of encountering these species in the project area would be lowest during summer. The months of March and April would be least favorable because North Atlantic right whales are expected to migrate northward in shallow waters along the North Carolina coast during this period. Whether or not seasonal restrictions on dredging are implemented, measures to minimize possible vessel interactions with endangered whales are likely to be required by the NMFS.

8.5 SYNTHESIS

The data collected, analyses performed, and simulations conducted for this study indicate that proposed sand dredging at sites evaluated on the OCS offshore North Carolina should have minimal environmental impact on fluid and sediment dynamics and biological communities. Short-term impacts to benthic communities are expected due to the physical removal of borrow material, but the potential for significant cumulative benthic impacts is remote. Additionally, no cumulative effects to any of the pelagic groups are expected from potential sand mining operations.

Minimal physical environmental impacts due to potential sand dredging operations (two primary dredging configurations) have been identified through wave and sediment transport simulations. The significance of changes to longshore transport along the modeled shoreline resulting from dredging proposed borrow sites to their maximum design depths was determined by comparing actual change in transport potential between existing and post-dredging conditions to a significance envelope of one-half the standard deviation ($\pm 0.5\sigma$) along the shoreline. Under representative wave conditions for each of the model grids offshore Dare County, North Carolina, it was determined that no significant changes in longshore sediment transport potential would result from modeled borrow site configurations, where Sites 3 west and 3 east were modeled separately. For sites dredged simultaneously, the impacts were estimated to exceed the $\pm 0.5\sigma$, and therefore would require mitigation along the affected shoreline or a redesign of the borrow site configuration, likely a reduction in maximum design depth at one of the sites. Because minor impacts to wave and sediment transport dynamics and biology may occur under conditions similar to those imposed in the present study, additional data collection and analysis may be required for a specific sand extraction scenario to determine the extent of impacts.

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