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FINAL REPORT

ENVIRONMENTAL SURVEYS OF POTENTIAL BORROW AREAS ON THE CENTRAL EAST FLORIDA SHELF AND THE ENVIRONMENTAL IMPLICATIONS OF SAND REMOVAL FOR COASTAL AND BEACH RESTORATION

Contract Number 1435-01-00-CT-31044

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FINAL REPORT

ENVIRONMENTAL SURVEYS OF POTENTIAL BORROW AREAS ON THE CENTRAL EAST FLORIDA SHELF AND THE ENVIRONMENTAL IMPLICATIONS OF SAND REMOVAL FOR COASTAL AND BEACH RESTORATION

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

Other CSA personnel who contributed to the project included Mr. David B. Snyder, who served as Chief Scientist for the soft bottom field surveys and northern area hard bottom survey; authored the hard bottom and fishes sections; and incorporated sections from other authors concerning infauna, soft-bottom epifauna, and discussion into the remainder of Section 6.0 (Biological Field Surveys) that he authored. Dr. Luis M. Lagera, Jr. was responsible for the spatial data files and exclusionary mapping. Dr. Alan D. Hart led the sampling design and statistical analyses for the biological data. Mr. Stephen T. Viada wrote the sections on sea turtles and marine mammals, and Dr. Neal W. Phillips reviewed those sections. Mr. Frank R. Johnson served as Operations Manager for the soft bottom field surveys. Mr. Paul S. Fitzgerald was Chief Scientist for the southern area hard bottom survey. Mr. Terry W. Stevens served as Operations Manager for the hard bottom surveys. Mr. Frederick B. Ayer, III and Mr. Lynwood R. Powell, Jr. directed operations for the field surveys. Ms. Karen Stokesbury assisted in literature and data collection. Ms. Melody B. Powell provided editorial assistance. Ms. Deborah Raffel supervised CSA support staff during production 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 2.2.5 (Waves and Wave-Generated Currents), 2.2.6 (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 (Florida Current and Eddies), 2.2.2 (Wind-Generated Currents and Upwelling), 2.2.3 (Tidal Currents), 2.2.4 (Storm-Generated Currents), 5.1 (Currents and Circulation), and 7.3 (Currents and Circulation). Ms. Elizabeth Hunt was responsible for report compilation and editorial assistance during production of the report.

Personnel from Barry A. Vittor & Associates, Inc. (BVA) contributing to the project included Dr. Barry A. Vittor, who served as Manager of BVA's responsibilities for the field surveys and report. Mr. Tim D. Thibaut authored the subsection in Section 2.3.1.1 concerning soft bottom infauna and epifauna, and Section 7.5.3.1 (Potential Soft Bottom Benthic Effects) of the report, with assistance from Dr. Vittor. In addition, Mr. Thibaut wrote Sections 6.3.3.1 (Infauna), 6.3.3.2 (Soft Bottom Epifauna), and 6.4 (Discussion). Mr. J. Dobbs Lee served as Scientist during both soft bottom surveys. Ms. Linda W. Sierke supervised personnel associated with taxonomic identifications. Ms. Robbin R. Alley served as BVA's Data Manager.

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ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
AFB	Air Force Base
ASTM	American Society for Testing and Materials
BVA	Barry A. Vittor & Associates, Inc.
CAN1	First Canonical Variate
CAN2	Second Canonical Variate
CCCL	Coastal Construction Control Line
C-CORE	Centre for Cold Ocean Resources Engineering
CDN	Coastal Data Network
CFR	Code of Federal Regulations
CSA	Continental Shelf Associates, Inc.
CTD	conductivity, temperature, and depth
DGPS	differential global positioning system
DNR	Department of Natural Resources
DOMES	Deep Ocean Mining Environmental Study
EA	Environmental Assessment
EFH	Essential Fish Habitat
EIS	Environmental Impact Statement
ESA	Endangered Species Act
FAU	Florida Atlantic University
FDEP	Florida Department of Environmental Protection
FGS	Florida Geological Survey
FKNMS	Florida Keys National Marine Sanctuary
FMP	Fishery Management Plan
FMRI	Florida Marine Research Institute
HAPC	Habitat Area of Particular Concern
ICONS	Inner Continental Shelf Sediment and Structure
LADS	Laser Assisted Depth Sounding
LPIL	lowest practical identification level
mcm	million cubic meters
mcy	million cubic yards
MESA	Marine EcoSystems Analysis
MLW	mean low water
MMS	Minerals Management Service
NAD	North American Datum
NAVD	North American Vertical Datum
NDBC	National Data Buoy Center
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
OBCS	Office of Beaches and Coastal Systems
OCS	Outer Continental Shelf
ODMDS	Ocean Dredged Material Disposal Site
ppt	parts per thousand
REF/DIF-S	REFraction/ DIFfraction model
REMOTS^{TM} System	Remote Ecological Monitoring of the Seafloor
RMS	Root-Mean-Square
SAB	South Atlantic Bight
SAFMC	South Atlantic Fishery Management Council
SCEMAD	Strategic Cumulative Effects of Marine Aggregates Dredging

List of Abbreviations (Continued)

SEAMAP-SA	Southeast Area Monitoring and Assessment Program-South Atlantic
STWAVE	STeady-state spectral WAVE model
SWAN	Simulation of WAves Nearshore
TN DOER	Dredging Operations and Environmental Research Technical Notes
USACE	U.S. Army Corps of Engineers
U.S.C.	United States Code
USC&GS	U.S. Coast and Geodetic Survey
USDOI	U.S. Department of the Interior
USFWS	U.S. Fish and Wildlife Service
UTM	Universal Transverse Mercator
WES	Waterways Experiment Station
WIS	Wave Information Study

1.0 INTRODUCTION

The U.S. Department of the Interior (USDOI), Minerals Management Service (MMS) funded the project titled "Environmental Surveys of Potential Borrow Areas on the Central East Florida Shelf and the Environmental Implications of Sand Removal for Coastal and Beach Restoration." This document is the Technical Report for the project.

1.1 BACKGROUND

1.1.1 Coastal Interests in OCS Sand

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

Considering future beach nourishment needs, renourishment maintenance cycles, and anticipated storms, coastal jurisdictions recently have become more interested in sand resources seaward of State waters for several reasons. There is increasing awareness that sand is a valuable resource and should be carefully managed as such. Onshore sources of suitable sand that were once abundant are becoming scarce due to deposit depletion, competing uses, and urban development. For ambitious nourishment projects, transporting sand from nearshore areas was found to be far more economical than trucking sand from upland sources (Freedenberg et al., 1995b). Like onshore sources, nearshore sand resources often are limited, diminishing in supply, and/or polluted, necessitating the need for alternative deposits that exist farther offshore. Using offshore deposits provides the important benefit of adding sand to the beach/nearshore system, rather than simply moving sand from one part of the system (nearshore) to another (beach). Furthermore, sand resources in Federal waters may be environmentally preferable due to concerns that extraction of large quantities of sand and gravel from nearshore sites can change the bathymetry of an area and result in modifications to existing physical oceanographic conditions. In relatively shallow nearshore waters, alterations to local current and wave regimes can have drastic consequences in terms of erosion and accretion. From a biological standpoint, excavation of sand resource areas farther from the shoreline may prove to have less adverse impacts on essential fish habitats than sites closer to shore (Jordan, 1999).

1.1.2 MMS Activities

The MMS is responsible for managing exploration and development of mineral resources on submerged Federal OCS lands. Among MMS missions is the need to develop approaches for managing the Nation's OCS mineral resources in an environmentally sound and safe manner. The MMS has a strong environmental mandate and is required to conduct environmental studies to obtain information useful for decisions related to marine mineral activities. Guidelines for protecting the environment stem from a wide variety of laws, including the OCS Lands Act, National Environmental Policy Act (NEPA), Endangered Species Act (ESA), Marine Mammal Protection Act, National Historic Preservation Act, Clean Water Act, Magnuson-Stevens Fishery Conservation and Management Act (Sustainable Fisheries Act), and others. Existing rules and regulations governing domestic marine mining provide a framework for comprehensive environmental protection during prospecting and scientific research activities and post-lease operations (e.g., 30 Code of Federal Regulations [CFR] Parts 280, 281, and 282).

Anticipating that requests for sand will increase significantly due to beach nourishment and storm protection needs, the MMS is ensuring that environmental management processes will be expedited when OCS sand resources are most needed. Under Public Law 103-426, the MMS has authority to convey rights to OCS sand, gravel, or shell resources for shore protection, beach or wetland restoration projects, or construction projects funded in whole or part or authorized by the Federal Government. As a result of the Water Resource Development Act of 1999, the MMS does not assess fees to any State or local government agency for OCS sand used in beach nourishment, shore protection, or coastal wetland restoration projects (MMS, 1999b), which furthers coastal interests in OCS sand. The MMS has provided Federal sand for beach nourishment projects in Florida, Louisiana, Maryland, New Jersey, and Virginia.

The MMS has been working with coastal States along the Atlantic Ocean and Gulf of Mexico to identify sand resources. Cooperative agreements and matching funds have allowed the MMS and States to conduct geological studies focused on locating sand sources that are compatible for beach nourishment and storm protection projects.

The MMS also has funded physical/biological studies offshore coastal States so that environmental information is available in a timely manner for prudent decisions regarding sand resources. Results will be used by the MMS to fulfill its environmental requirements when specific requests for Federal sand are received from States, local jurisdictions, or other Federal agencies.

1.1.3 MMS and State of Florida

The MMS has been actively working with the State of Florida to identify and convey OCS sand for beach nourishment. The MMS initiated a Federal/State partnership in July 1994 with the State of Florida to identify offshore areas that may contain sand resources suitable for beach nourishment (MMS, 1999a). The MMS has conveyed OCS sand to Brevard County, Duval County, and Patrick Air Force Base (Hartgen, 2001).

The MMS and State of Florida also cooperated in an outreach effort directed at organizations involved in beach nourishment and coastal issues. A panel presentation titled “Interagency Cooperation Regarding Offshore Sand Resources” occurred 3 February 2000 at the 13th Annual National Conference on Beach Preservation Technology in Melbourne, Florida. Presentations were given by the MMS titled “A Biological/Physical Dredging Impact Study Offshore Central Florida” (Drucker, 2000) and by the Florida Geological Survey (FGS) titled “Preliminary Identification of Sand Resources in Federal Waters Along the Central Florida East Coast” (Freedenberg et al., 2000a).

The MMS and FGS have been focusing on the geology of a region 3 to 8 miles offshore of Brevard, Indian River, St. Lucie, and Martin Counties along the central east coast of Florida. Over 58 miles of sandy beaches are eroding along this 90-mile stretch of coastline (MMS, 1999a). Reports for Years 1 (Freedenberg et al., 1995a,b; Hoenstine et al., 1995), 2 (Freedenberg et al., 1997), 3 (Freedenberg et al., 1999), and 4 (Freedenberg et al., 2000b) have resulted from the MMS/FGS efforts. The goal of the multi-year cooperative agreement was to locate OCS sands suitable for beach restoration (Freedenberg et al., 2000a). Results of the FGS investigations were intended to form the geological basis for conducting the physical/biological study, which is the topic of this document, to evaluate potential impacts from dredging in sand resource areas.

1.2 STUDY AREA

The study area for the physical/biological project encompassed OCS waters seaward of the Federal/State boundary offshore of Brevard, Indian River, St. Lucie, and Martin Counties (Figure 1-1).

1.3 STUDY PURPOSE AND OBJECTIVES

The MMS specified the purpose and objectives of this physical and biological study. The primary purpose of the study was to address environmental concerns raised by the potential for dredging OCS sand offshore the central east coast of Florida and to document the findings in a technical report. Environmental information was collected and compiled to assist the MMS in making future decisions relative to negotiated agreements (non-competitive leases), NEPA documents (Environmental Assessments and Environmental Impact Statements), and other regulatory requirements concerning Federal sand deposits off Florida.

Primary environmental concerns focused on physical and biological components of the OCS environment. To this end, the MMS identified five study objectives at the beginning of the project:

Physical Objectives

- Wave Modifications: Evaluate potential modifications to waves and currents in the study area due to offshore dredging within potential sand resource areas.
- Sediment Transport Patterns: Evaluate impacts of dredging in Federal waters and consequent beach nourishment in terms of potential alterations in sediment transport patterns and sedimentary environments, and impacts to local shoreline processes.

Biological Objectives

- Benthic Ecological Conditions: Characterize benthic ecological conditions in and around potential sand resource areas identified by the MMS/FGS cooperative effort.
- Benthic Infaunal Evaluation: Evaluate benthic infauna resident in potential sand resource areas and assess potential effects of offshore dredging activity on these organisms, including an analysis of recolonization periods and success following cessation of dredging activities.
- Project Scheduling Considerations: Evaluate times for dredging in the sand resource areas relative to transitory pelagic species.

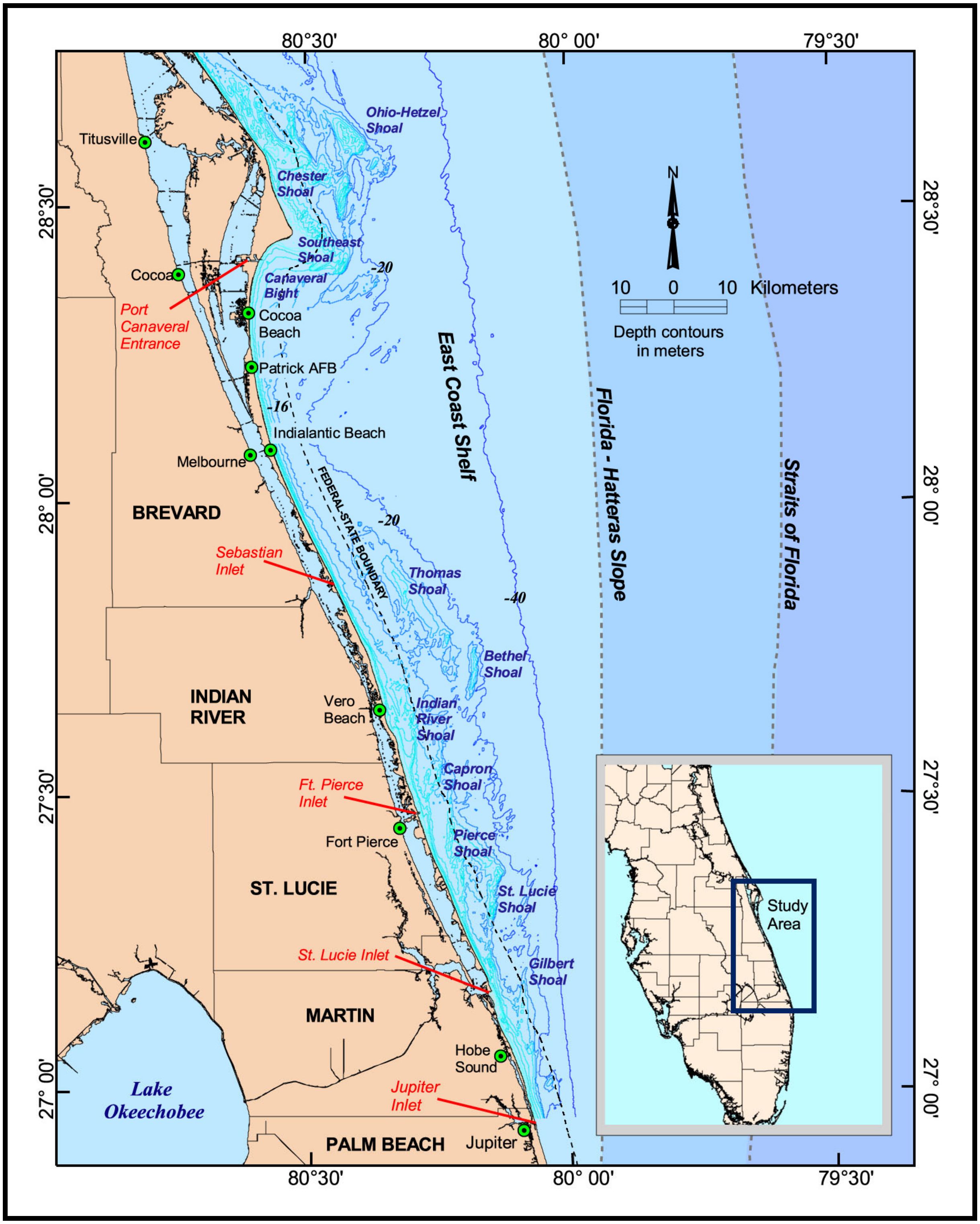

Figure 1-1. Central east Florida study area and key geographical features.

1.4 STUDY APPROACH

1.4.1 Sand Resource Area and Borrow Site Locations and Characteristics

Since 1994, the MMS has provided funds to the FGS to collect seismic, grab, and vibracore data for the purpose of identifying sources of sand in Federal waters offshore Martin, St. Lucie, Indian River, and Brevard Counties (see Section 1.1.3). In 2000, the MMS requested that the FGS provide recommendations for potential sand resource areas offshore the four counties based on geological study results and best available information, even though additional geological sampling and interpretation may be needed in the future. The FGS subsequently identified eight sand resource areas that formed the basis for conducting this physical/biological study (Figure 1-2). Areas A1 and A2 were offshore Brevard County near Cape Canaveral, Areas B1 and B2 were offshore of the line between Brevard/Indian River Counties, Areas C1 and C2 were offshore of the line between St. Lucie/Martin Counties, and Areas D1 and D2 were offshore south Martin County.

In 2001, the MMS requested that a ninth sand resource area be included only as part of the biological studies. This ninth sand resource area is referred to as Area A3 in this report. Area A3 is located inshore of Area A2, is just seaward of the Federal-State boundary, and is small relative to the other eight sand resource areas (Figure 1-2). As directed by the MMS, biological surveys were conducted in and near these nine sand resource areas to characterize benthic ecological conditions. Because monitoring surveys of actual sand mining operations were not to be conducted, the biological assessment was based only on the field characterization surveys and existing literature.

In contrast to the biological studies, the MMS requested that the physical processes studies focus on borrow sites within sand resource areas where compatible sand characteristics and appropriate sand volumes were available to meet local beach nourishment requirements. Six potential sand borrow sites within five of the nine resource areas (Figure 1-2) were evaluated to determine the potential impacts of offshore sand mining for beach replenishment (see Section 7.0). Although Areas A1, B1, B2, C1, and D2 were designated as ones with greatest potential, it is possible that sand could be dredged from intervening offshore sites. Borrow sites in Areas A2, A3, C2, and D1 were not included in the physical processes analyses. For Area A2, no shoals are present on the seafloor, signifying low priority as a sand borrow site. As long as numerous sand shoals exist as potential borrow sites within the geographical area, it is recommended that holes not be excavated on the shelf surface. Area A3 was selected for biological analyses only. In Area C2, the quantity of sand available for beach nourishment is small (<1 million cubic meters [mcm]) relative to basic replenishment needs. At Area D1, water depths are in excess of 30 m, making potential dredging operations more complicated and costly. For the remaining potential sand resource areas, each has specific geological and geographical characteristics that make it viable as a sand target for specific segments of coast. These sand resource areas are very similar geologically (medium-to-coarse sand size ridge deposits with relief of 2 m or more and resource volumes of at least 1 mcm).

The amount of dredging that occurs at any site is a function of Federal, State, and local requirements for beach replenishment. It is nearly 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 MMS and State personnel. Preliminary analysis of short-term impacts (storm and normal conditions) at specific locations along the coast

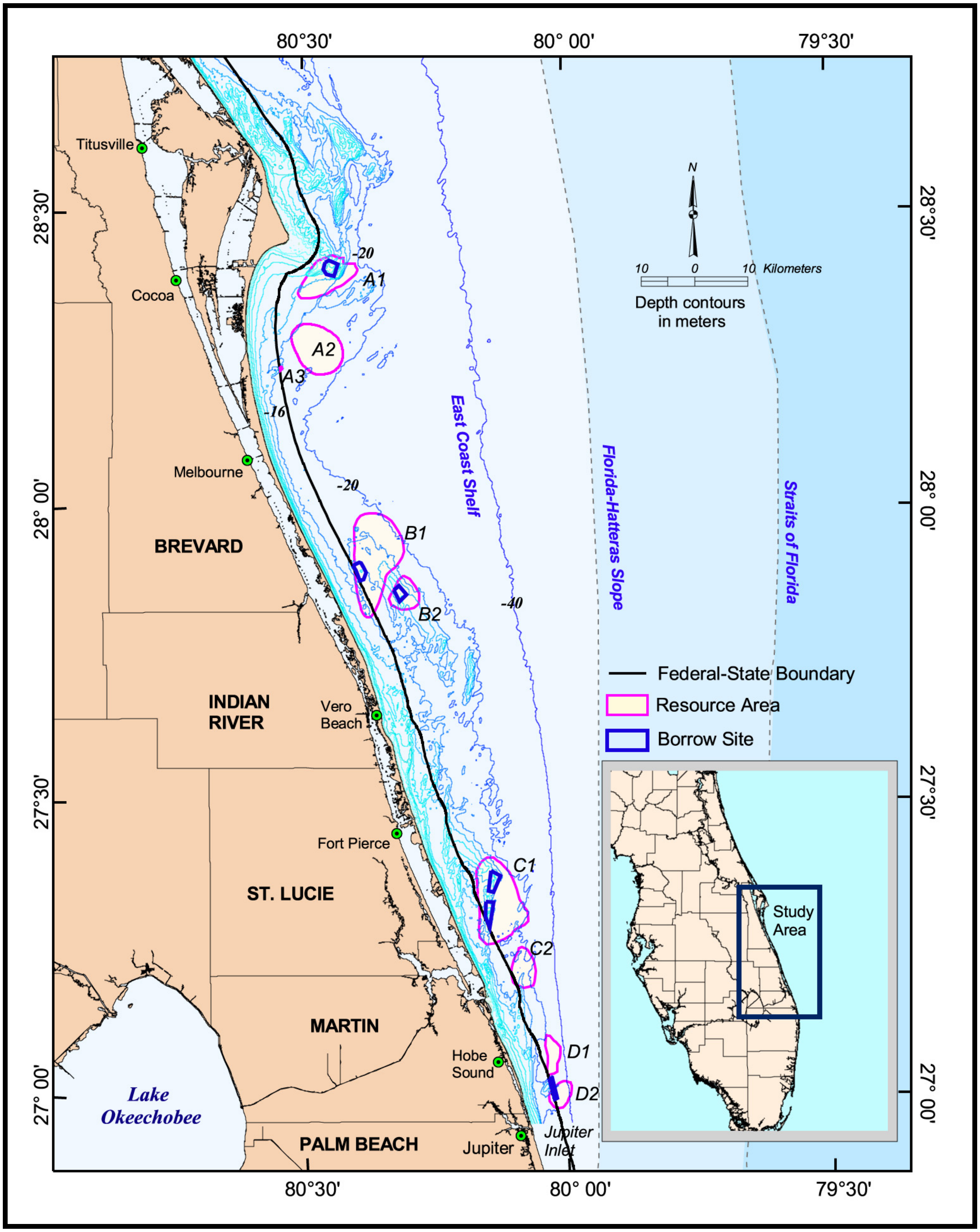

Figure 1-2. Sand resource areas and borrow sites relative to the Federal-State boundary.

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 indicate that a replenishment interval of about 10 to 30 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 without 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 good sand resource management practice to dredge the leading edge of a migrating shoal because infilling of dredged sites occurs more rapidly at these locations (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, 1976). As such, average shoal relief is a reasonable threshold for maintaining environmentally-sound sand extraction procedures.

For sand resource areas within the study area, maximum shoal relief was on the order of 5 to 6 m, and average shoal relief was about 2 to 3 m. Although modern beach replenishment practice varies depending on geographical location and level of funding for the central east Florida 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 A1, a 5.39×10^6 m^2 borrow site was defined based on shoal morphology (Figure 1-2). Bathymetric data and geological samples indicated a maximum excavation depth of 12 m, resulting in a 13.6 mcm extraction scenario; median grain diameter for the deposit is 0.32 mm (Table 1-1). The same procedure was used for borrow sites at the other selected sand resource areas. The borrow site in Area B1 encompassed 4.62×10^6 m^2 of seafloor to a depth of 15 m, resulting in 11.0 mcm of sand. The borrow site for Area B2 covers 3.48×10^6 m^2 of seafloor to a maximum excavation depth of 13 m, and it contains 7.6 mcm of sand. For the northern borrow site in Area C1 (C1 north), surface area encompassed 5.16×10^6 m^2. The maximum excavation depth was 12 m, resulting in 5.8 mcm of sand. The southern borrow site in Area C1 (C1 south) covers approximately 4.71×10^6 m^2 of seafloor. For an excavation depth of 12 m, the resulting sand volume is 8.8 mcm. For the southernmost sand resource area (D2), the sand borrow site is quite small at approximately 2.25×10^6 m^2 of seafloor. For an excavation depth of 20 m, the resulting sand volume is 4.1 mcm. 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 wave and sediment transport 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 central east Florida.

Borrow Site	Borrow Site Surface Area (x 10^6 m^2)	Maximum Excavation Depth (m)	Borrow Site Sand Volume (x 10^6 m^3)	D10 (mm)	D50 (mm)	D90 (mm)
A1	5.39	12	13.6	0.70	0.32	0.21
A2	No Shoals	No Shoals	No Shoals	-----	-----	-----
A3	Biology Only	Biology Only	Biology Only	-----	-----	-----
B1	4.62	15	11.0	1.15	0.60	0.28
B2	3.48	13	7.6	1.49	0.47	0.25
C1 (north)	5.16	12	5.8	1.96	0.61	0.26
C1 (south)	4.71	12	8.8	0.62	0.29	0.18
C2	Too Small	Too Small	Too Small	-----	-----	-----
D1	Depth Limited	Depth Limited	Depth Limited	-----	-----	-----
D2	2.25	20	4.1	0.59	0.31	0.20

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

1.4.2 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 borrow sites 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 borrow sites. 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 conditions and post-dredging impacts provided a means of documenting modifications to waves as they crossed the sand resource areas.

1.4.3 Sediment Transport Patterns

The goal of this study element was to predict changes in sediment transport patterns resulting from sand dredging operations using numerical information generated from wave transformation modeling, combined with offshore current data. Because localized flow patterns over shoals may have significant impact on ecological conditions in the offshore sand resource areas, total currents were measured east of Sebastian Inlet at Areas B1 and B2 using an Acoustic Doppler Current Profiler (ADCP). Existing current measurements were analyzed to document temporal variations in flow throughout the study area, whereas ADCP measurements were used to examine spatial variations throughout the water column (detailed in Section 5.0). Sediment transport rates were quantified for sand borrow sites using an analytical approach, whereas transport rates at the shoreline were determined numerically using output from wave transformation numerical modeling.

Historical shoreline and bathymetric data were compiled to document regional sediment transport patterns over a 40- to 50-yr time period. Net changes in sediment erosion and deposition on the shelf surface provided a direct method for identifying patterns of sediment transport and quantifying net rates of change throughout the sand resource areas. These data also were used to verify numerical results for direction and magnitude of sediment transport.

1.4.4 Benthic Ecological Conditions

The goal of this study element was to characterize benthic ecological conditions in and around the sand resource areas. Existing literature and data were searched, collected, analyzed, and summarized to characterize the ecological environment and to form the foundation for biological field survey design. Biological field surveys were conducted to characterize infauna, soft bottom epifauna and demersal fishes, hard bottom epibiota and demersal fishes, sediment, and water column parameters.

1.4.5 Benthic Infaunal Evaluation

The goal of this study element was to assess potential effects of offshore dredging on benthic infauna and analyze recolonization periods and success following cessation of dredging activities. Existing literature and data on dredging effects were used in conjunction with biological field survey results to examine potential benthic effects and recolonization in the sand resource areas. Monitoring surveys of actual sand mining operations were not to be conducted in the areas to determine impacts.

1.4.6 Project Scheduling Considerations

The goal of this study element was to evaluate 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 concerning seasonal occurrence of pelagic species and potential impacts from dredging was used to evaluate project scheduling considerations for pelagic fishes, sea turtles, and marine mammals.

1.5 DOCUMENT ORGANIZATION

This document was organized into nine major sections as follows:

- Introduction
- Environmental Setting
- Regional Geomorphic Change
- Assessment of Wave Climate Impact by Offshore Borrow Sites
- Circulation and Offshore Sediment Transport Dynamics
- Biological Field Surveys
- Potential Effects
- Conclusions
- Literature Cited

In addition to the main document, appendices were prepared in support of many analyses presented in the report. Furthermore, an Executive Summary, a Technical Summary, and a Non-Technical Summary will be prepared as separate documents to provide brief study descriptions for audiences including managers, researchers, and the general public.

2.0 ENVIRONMENTAL SETTING

Florida's east coast is approximately 800 km long and represents part of the passive, slowly subsiding eastern North American continental margin (Klitgord et al., 1988). It lies within the Coastal Plain Physiographic Province that stretches along the Atlantic and Gulf Coasts of North America from Long Island to Mexico and is underlain by thick sedimentary sequences of Tertiary and Quaternary age, with the oldest of the exposed rocks in this region belonging to the Eocene-Ocala Group (Meisburger and Duane, 1971). Coastal features are represented by a series of low barrier beaches and islands, and include the Cape Canaveral peninsula, one of the largest cuspate forelands in the world (Figure 2-1). The barrier islands are punctuated by numerous inlets, providing exchange of sediment and water between estuaries and the continental shelf, primarily as a function of tide. The project site is located along the central portion of the east coast of Florida, extending from about 80°36'50"W, 28°37"49'N (False Cape) to about 80°04'15"W, 26°56'40"N (Jupiter Inlet). This area encompasses approximately 200 km of exposed coastline that includes five major inlets (Port Canaveral, Sebastian, Fort Pierce, St. Lucie, and Jupiter). The offshore portion of the study area extends east from the high-water shoreline across the southernmost section of the East Coast Shelf (known as the Florida Continental Shelf) and is bounded to the east by the steep Florida-Hatteras Slope (Figure 2-1). Although the offshore Federal-State jurisdictional boundary marks the direct landward limit of the study area, the ultimate use of sand extracted from the OCS is for beach replenishment along the central east Florida outer coast. Consequently, a description of the environmental setting from the outer coast to the OCS is pertinent for addressing the overall study purpose.

Florida beaches historically have attracted numerous visitors and are responsible for a majority of tourism in the State (Pilkey et al., 1984). According to the Florida Department of Environmental Protection, beaches have attracted 14 million permanent residents to the State, 75% of which live within 10 miles of the coast (State of the Coast Report, 1996). Recent increases in tourism have led to extensive shorefront development and growth of coastal communities. The degree of development along different portions of the coastline varies greatly, but the maintenance of beaches is of vital social and economic importance to the communities. A combination of natural shoreline retreat and storm damage has provided incentive for beachfront property owners and communities to install seawalls, sloping revetments, and groins, in addition to supporting beach nourishment (Pilkey et al., 1984).

Most of the barrier islands in the study area have been nourished periodically along portions of their outer coasts since the 1970s. The need for sand to replenish eroding beaches continues to be an area of concern for local, State, and Federal resource agencies, prompting the exploration and environmental evaluation of offshore resource sites for future use. Beach nourishment has been combined with structural development to further prevent erosion problems and stabilize Federal entrances. Engineered inlets were created at four of the five entrances within the study area, and each was armored with rock jetties on both banks by 1954. Structure placement and inlet development have contributed to the interruption of natural littoral processes within the study area, resulting in erosional "hot spots" on the downdrift sides of entrances. Estimated volumes and locations of beach nourishment activities as well as the history of structure development are summarized in Section 3.1 of this report.

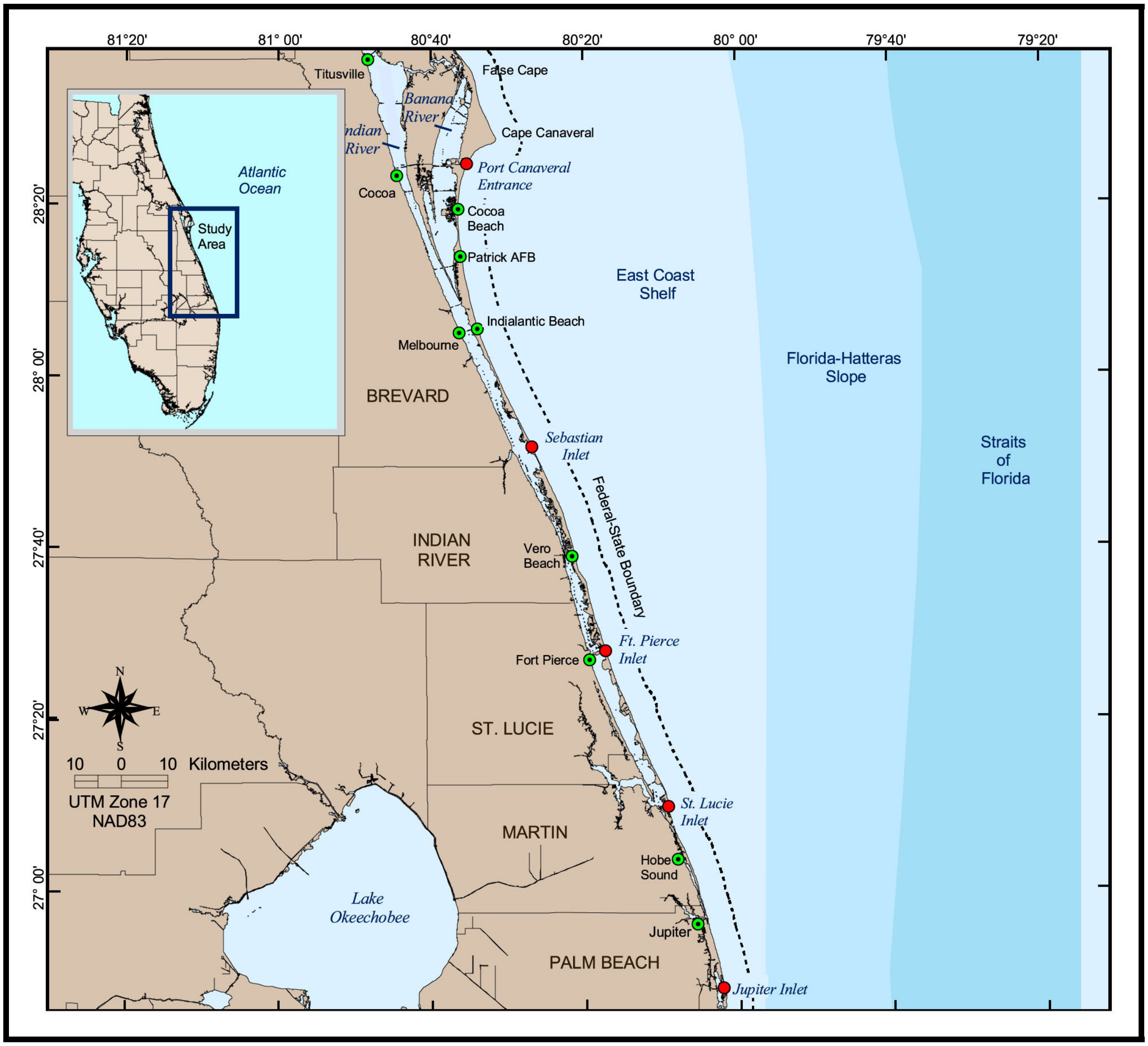

Figure 2-1. Central east Florida study area, including inlet locations and the Federal-State boundary.

Within the northern portion of the study area, sandy beaches exist along the base of the Canaveral Peninsula beach ridge complex. Field and Duane (1974) characterized beach sediments in this region using 24 samples collected along the outer coast between False Cape and Melbourne Beach (Figure 2-2). Their study found that areal beach sediment was composed primarily of coarse to fine grained sands, with a high percentage of shell fragments mixed throughout. Sediment size tends to vary considerably along the outer coast, with finest sediments located just south of Cape Canaveral. Lateral transport by littoral currents and onshore transport during optimal wave conditions are the major processes influencing the composition of beach sands in this area (Field and Duane, 1974). Grain-size variations observed within the region are the result of changes in shoreline

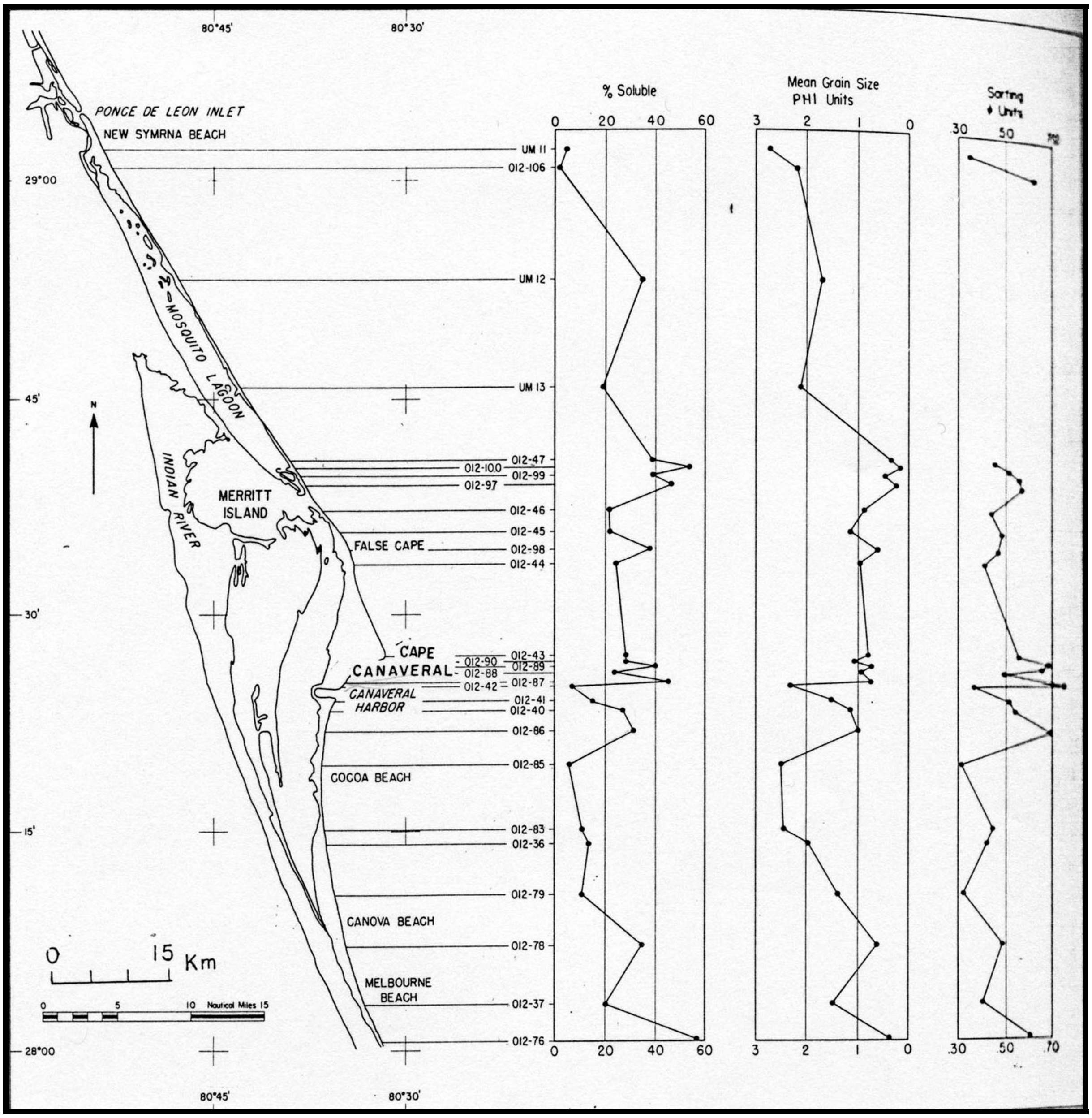

Figure 2-2. Percent soluble, mean grain size, and sorting for beach samples showing the direct influence of shell material on textural parameters (from Field and Duane, 1974).

orientation and exposure, in addition to the availability of offshore materials, with increases in sediment grain size being directly related to increases in the percentage of shell fragments (Field and Duane, 1974). Stauble and McNeill (1985) documented similar trends and noted that the shoreline on the south side of the Cape exhibits noticeable changes in sand grain size, shell content, and beach slope than that observed on beaches to the north. Beaches close to the south side of the Cape are characterized by broad, flat slopes with fine-grained composition. Further south, beaches narrow, steepen, and become coarser-grained with an increase in shell fragments due to the increasing presence of local coquina outcrops (Field and Duane, 1974; Stauble and McNeill, 1985).

Clausner (1982) found that the shoals off the Cape cause wave refraction around the feature, creating a shadow zone that protects these finer-grained, flatly-sloping beaches from high energy waves. Sediment in this portion of the study area was characterized as calcareous quartzose sands, with coarser foreshore sands occurring near outcrops of the Anastasia Formation (Clausner, 1982). Morphology of the peninsula is dominated by a number of terraces aligned roughly parallel to the present coastline, which have been interpreted as forming during brief transgressions associated with the Wisconsinan glacial period (Field and Duane, 1974). The morphological pattern was interpreted as a series of seaward-building beach ridges (Figure 2-3; Field and Duane, 1974). Present coastal processes are maintaining the beaches and moving sand in a southward direction (Clausner, 1982). South of Port Canaveral, the shoreline rotates to a northwest-southeast orientation, characteristic of the general study area.

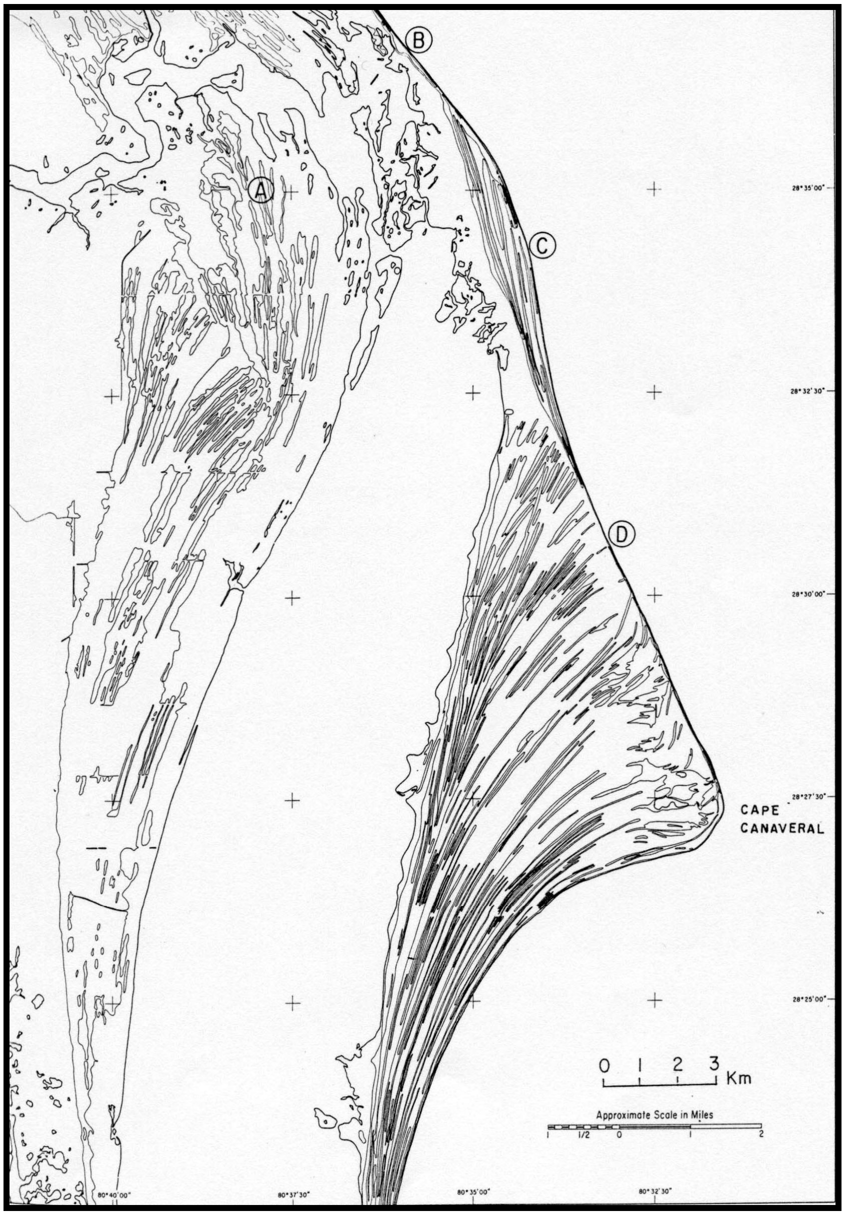

Figure 2-3. Canaveral Peninsula showing beach ridge orientations compiled from aerial photos and topographic maps (from Field and Duane, 1974).

The ocean shoreline from Port Canaveral south to Jupiter Inlet is composed of a continuous chain of five barrier islands that protect estuarine and coastal plain environments from direct wave attack. The islands are separated from each other and the mainland by five Federal entrances and the Intracoastal Waterway, which is made up of the Indian and Banana Rivers. Four of the five entrances within this section of coast are engineered, including Port Canaveral, Sebastian, Fort Pierce, and St. Lucie. Each of the entrances within the study area has been armored with rock jetties on both banks to control channel migration and maintain navigable entrance depths. Maintenance dredging also has been practiced periodically at all entrances to maintain channel navigability (Stauble and McNeill, 1985). Sand derived from dredging projects often is placed on south side beaches as nourishment material. Barrier islands comprising the chain in this region are relatively long and narrow, ranging from about 35 to 65 km in length and measuring on average less than 2 km in width. Foredunes are locally developed along various sections of the barrier islands, which prevents overwash and landward migration during storm events (Pilkey et al., 1984; Freedenberg et al., 1995b). The dunes have relatively low elevations, with heights generally ranging from about 2.5 to 3 m in most areas (Pilkey et al., 1984).

The outer coast along central east Florida is oriented primarily northwest-southeast, becoming north-south oriented within the southernmost portion of the project area. Beach sediments along this section of coast are composed primarily of medium- to coarse-grained sand with large quantities of carbonate mixed throughout (Meisburger and Duane, 1971). The median diameter of foreshore samples collected in this region averages about 0.43 mm (Figure 2-4; Hoenstine and Freedenberg, 1995). Beach sand is relatively well-sorted but contains large median size variations from one region to another. Quantities of shell material and alongshore processes controlling sediment distribution are the major factors influencing large size variations (Meisburger and Duane, 1971). All indurated sediments in the study area generally are assigned to the Anastasia Formation, which is regarded for the most part as Pleistocene in age but includes some recently cemented Holocene beach rock. The Anastasia underlies all modern beach sediments in the study area (Freedenberg et al., 1995b). State geological maps illustrate the general stratigraphy and surficial sediment classification for subaerial deposits within the study area (Figure 2-5). According to this classification scheme, most sediment comprising ocean beaches consist primarily of shelly sands and clays, with smaller areas of medium- to fine-grained sands and silts located on Cape Canaveral and south of St. Lucie Inlet. Stratigraphic maps of the area characterize the region as ranging from Pleistocene to Holocene age, with most of the coastline classified as Pleistocene or Pleistocene/Holocene.

2.1 OFFSHORE SEDIMENTARY ENVIRONMENT

Morphology of the continental margin offshore southeastern Florida reflects the influence of four separate shaping processes, including reef building during the Tertiary, deposition on the shelf in the littoral zones of the Pleistocene, erosion by the Florida Current, and deposition and shaping by bottom currents (Uchupi, 1969). Meisburger and Duane (1971) documented the Eocene and post-Eocene history within the study area as one of repeated invasions and retreats of the sea. Erosional unconformities and hiatuses in the Eocene column point to tectonic instability throughout that period. Analysis of seismic reflection profiles indicated an abrupt steepening of dip of some deep reflections, an apparent effect of a near-coast fault between Cape Canaveral and Fort Pierce (Meisburger and Duane, 1971). During the Pleistocene, central east Florida was alternately flooded and exposed to subaerial erosion, leaving a variable and sometimes complex series of sediment and erosional surfaces (Meisburger and Duane, 1971). During Pleistocene interglacial periods, marine sands were deposited in submerged areas and transgressive stratigraphic sequences were formed (Stauble and McNeill, 1985). The last major event was the advance of the Holocene sea across the upper continental slope and shelf, starting about 12,000 years ago and ending about 4,000 years ago (Curray, 1965; Milliman and Emery, 1968). Reworking of some marine sands deposited within interglacial periods has continued during the Holocene (Stauble and McNeill, 1985). Presently, a thick sedimentary section underlies the area, with Pleistocene sediments of the Anastasia Formation comprising much of the offshore subsurface sedimentary environment.

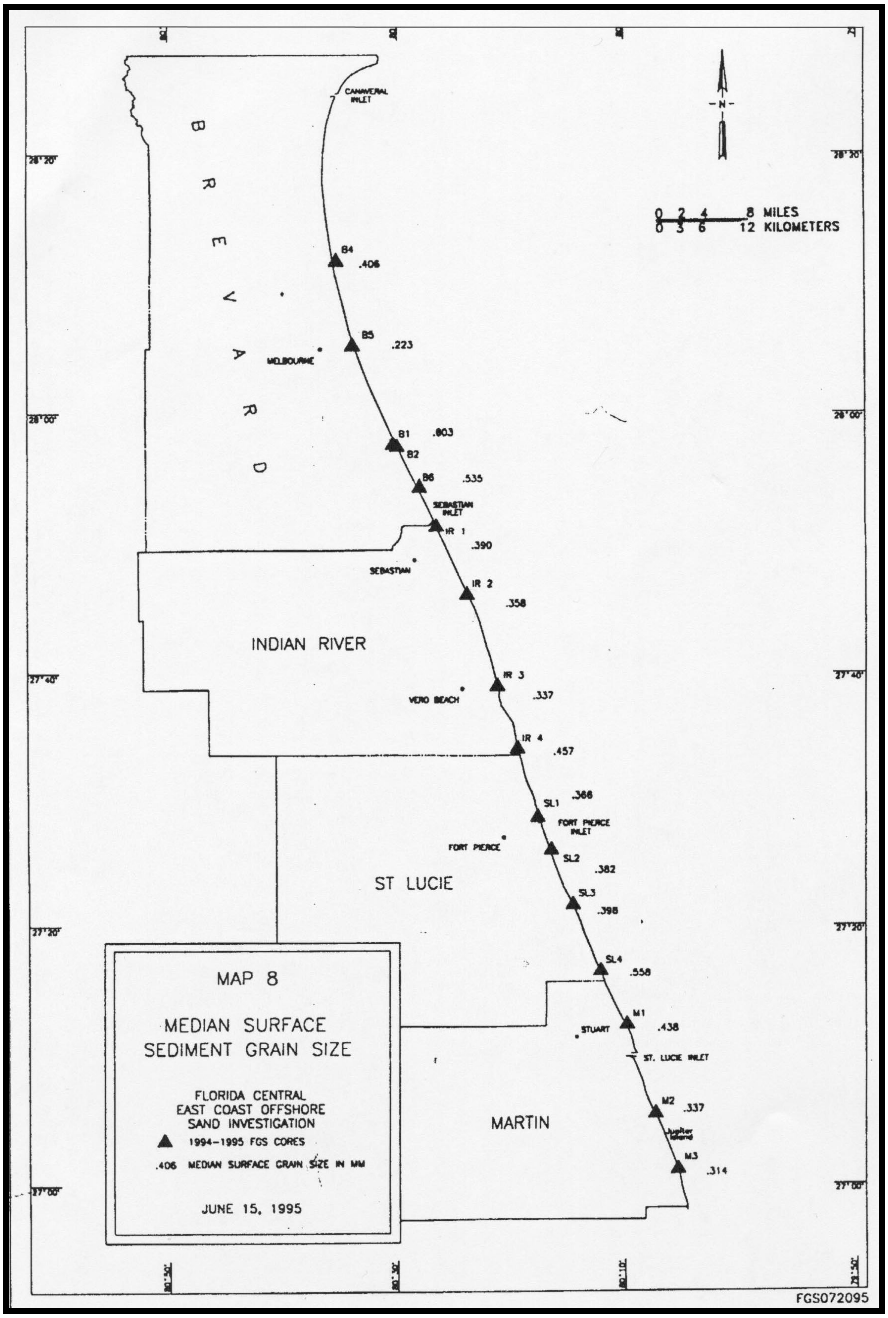

Figure 2-4. Median grain size of beach sediment collected between Brevard and Martin Counties (from Hoenstine and Freedenberg, 1995).

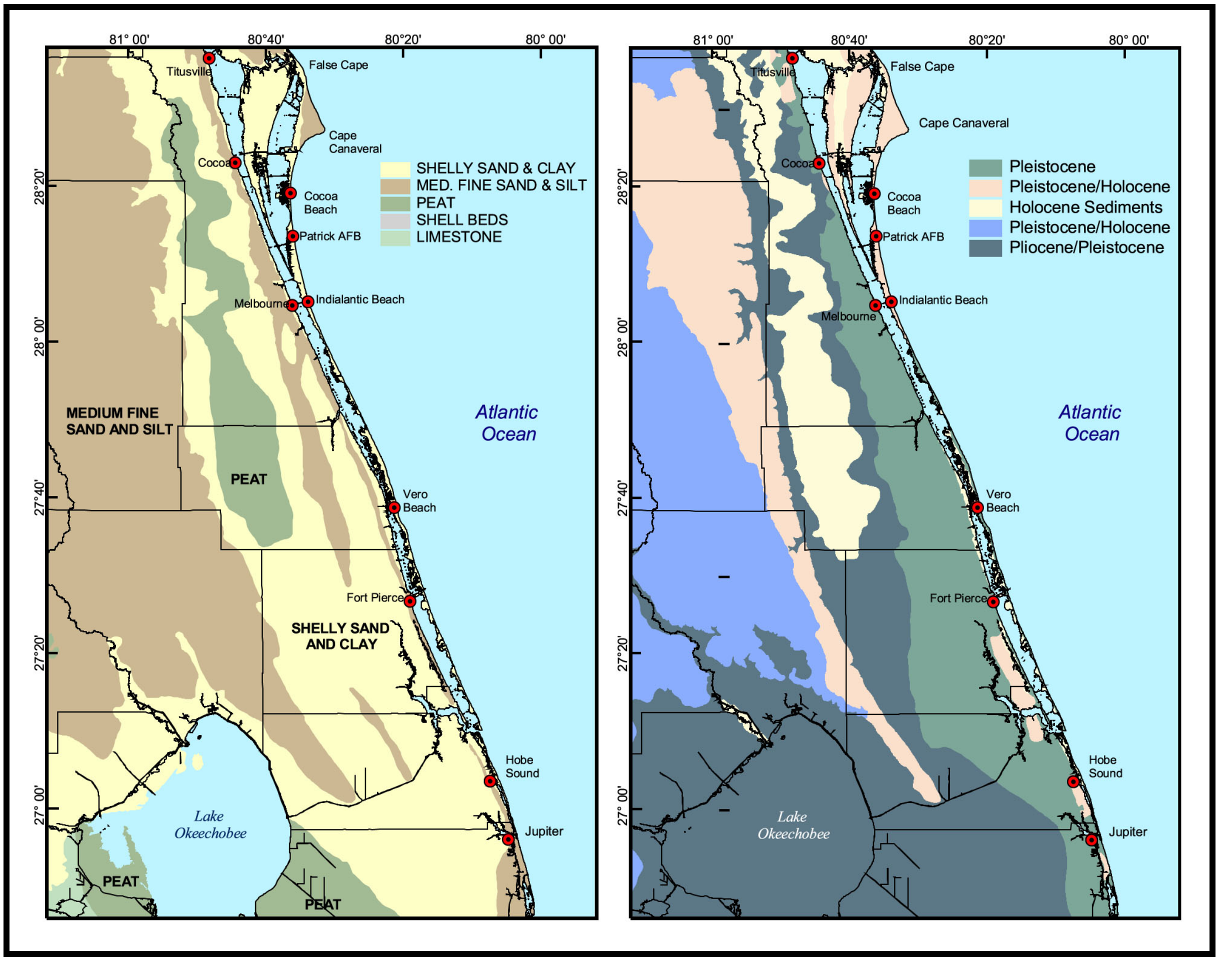

Figure 2-5. Surficial sediments and stratigraphy of central east Florida (adapted from the Florida Geological Survey digital data archive).

In some places, Anastasia rocks are overlain by quartzose sands of the Pamlico Formation, which locally attains thicknesses of 12 m but is usually much thinner (Meisburger and Duane, 1971).

Five physiographic provinces have been distinguished by Uchupi (1969) along the continental margin offshore eastern Florida based on bathymetric soundings. These provinces include the Florida Continental Shelf, the Florida-Hatteras Slope, the Straits of Florida, the Blake Plateau, and the Bahama Banks (Figure 2-6). The offshore portion of the study area is limited to the Florida Continental Shelf, which is the southernmost part of the East Coast Shelf. It is composed of strata lying at low angles and dipping generally easterly and southeasterly (Field and Duane, 1974). The continental shelf narrows dramatically from a maximum width of about 48 km near Cape Canaveral to a minimum of about 16 km in the southern extent of the study area as it merges with the Florida-Hatteras slope (Figure 2-6). This reduction in width is accompanied by a distinct increase in shelf steepness from north to south (Field and Duane, 1974). The Florida Continental Shelf has been classified into several morphologic zones, including an inner smooth zone extending from the shoreline out to a depth of about 16 m, a ridge zone (known as the Inner Shelf Plain) ranging from 16 to 40 m water depth, a second smooth zone (known as the Outer Shelf Plain) extending from 40 to 60 m water depth, and another deep ridge zone between -60 and -80 m (Uchupi, 1969). The inner ridge zone between 16 and 40 m water depth occurs in an area blanketed by relict terrigenous sands containing appreciable quantities of shell debris. Similar features also have been reported from other segments of the continental shelf off the U.S. east coast by Uchupi (1968). He has suggested that most of the ridges represent offshore bars formed during lower stands of sea level during the Pleistocene. He also suggested that some of the ridges may still be active at present, particularly during intense storms such as hurricanes. Ridges located within the outer ridge section at the shelf edge also are believed to be related to prior lower stands of sea level during the Pleistocene (Uchupi, 1969).

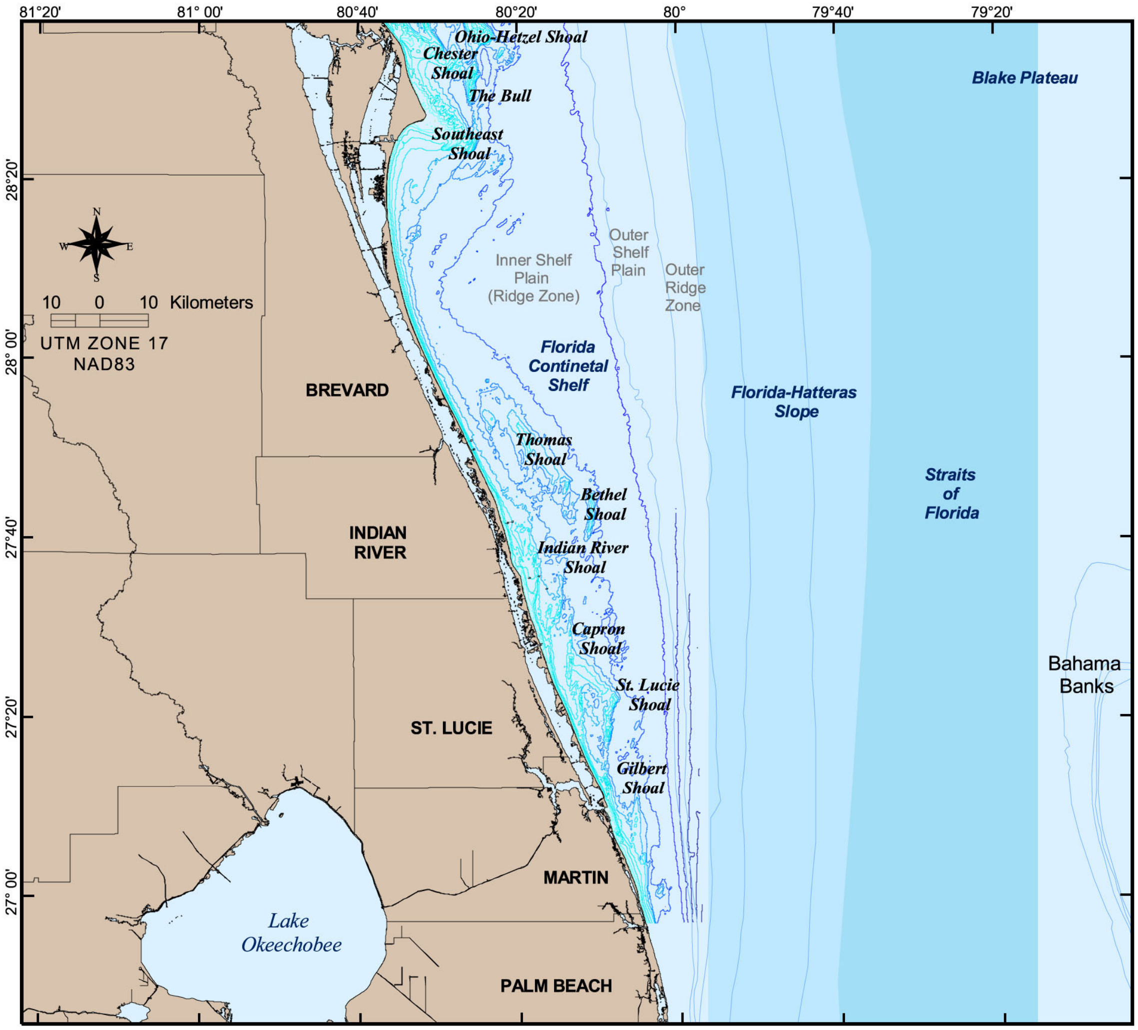

Figure 2-6. Physiographic provinces of the continental margin offshore central east Florida.

All sand resource areas defined for this study are located within the inner ridge portion of the continental shelf. Characteristics of the offshore sedimentary environment, specifically the numerous sand ridges found in this region, have been summarized by numerous investigators. Some of the more notable investigations that have been completed for the study area include early research performed as part of the Inner Continental Shelf Sediment and Structure (ICONS) Investigations completed by Meisburger and Duane (1971), Duane et al. (1972), and Field and Duane (1974), which characterized the morphology and sedimentary regime of linear sand shoals along the Florida Atlantic continental shelf. More recently, geological characterizations made by Stauble and McNeill (1985), Nocita et al. (1990), Amato (1993), Freedenberg et al. (1995b, 1997, 1999, 2000), and U.S. Army Corps of Engineers (USACE) (1999a) have added substantial detail to that obtained from early studies. The following sections use background information obtained from these sources in addition to recent sediment sampling to describe offshore deposits and their relationship to defined sand resource areas.

2.1.1 Seabed Morphology

The Florida Continental Shelf offshore central east Florida is characterized primarily by a well-developed shoreface zone, numerous cape-associated arcuate shoals, isolated or shoreface-attached linear sand ridges, and a gently sloping Outer Shelf Plain. These characteristics divide the shelf naturally into its major components, including the inner smooth zone associated with the shoreface region, the Inner Shelf Plain zone associated with sand shoals and ridges, and the Outer Shelf Plain. The most prominent geomorphic features throughout the region are offshore shoals and linear sand ridges, including Ohio-Hetzel and Chester Shoals in the north to Gilbert Shoal in the southern portion of the study area (Figure 2-6). Shoal morphology and frequency in this region varies considerably from north to south. Adjacent to Cape Canaveral, topography of the inner shelf is highly irregular, with large arcuate and isolated shoals extending southeast from False Cape and Cape Canaveral (Figure 2-7). South of the Canaveral shoal system, topography of the shelf becomes more subdued as it flattens south of Port Canaveral. From Sebastian Inlet south to Jupiter Inlet, shelf morphology again becomes more irregular, with numerous north-south trending linear shoreface-attached and isolated shoals dominating the structure of the shoreface and the inner shelf region (McBride, 1987).

The shoreface extends from the shoreline to about the 12-m depth contour. The character of this offshore zone varies considerably throughout the study area, as the influence of cape-associated and shoreface-attached linear shoals varies significantly. The shoreface is steepest north of Cape Canaveral, an area that has historically experienced relatively high rates of erosion due to south-directed littoral transport. South of this area and adjacent to Cape Canaveral, the shoreface becomes increasingly irregular as its configuration is interrupted by two shore-connected shoals. These two shoals, Southeast and Chester Shoals, merge from the shoreline on to the shoreface. South of Cape Canaveral to Sebastian Inlet, the shape of the shoreface becomes increasingly smooth and regular, making a gentle seaward dip and exhibiting relatively even contour spacing with minor irregularities out to the inner shelf plain. South of Sebastian Inlet, shoreface-attached linear shoals become more prevalent, creating a variable configuration seaward to the Inner Shelf Plain.

According to Meisburger and Duane (1971), surficial sediment comprising the upper shoreface (from the shoreline to about -6 m) was coarser, less well-sorted, and displayed greater variability than those found on the outer shoreface (from about 6 to 12 m water depth). Shallow nearshore sediment was composed of calcareous quartzose sand, with variations in size resulting from availability of a wide range of calcareous particle sizes (shell material). Bottom sediment of the lower shoreface was richer in quartz, finer, better sorted, and far more uniform in size than sediment found on the upper shoreface. Deeper shoreface deposits probably result from seaward transport of fine material winnowed from sand deposits in the high-energy surf zone (Meisburger and Duane, 1971).

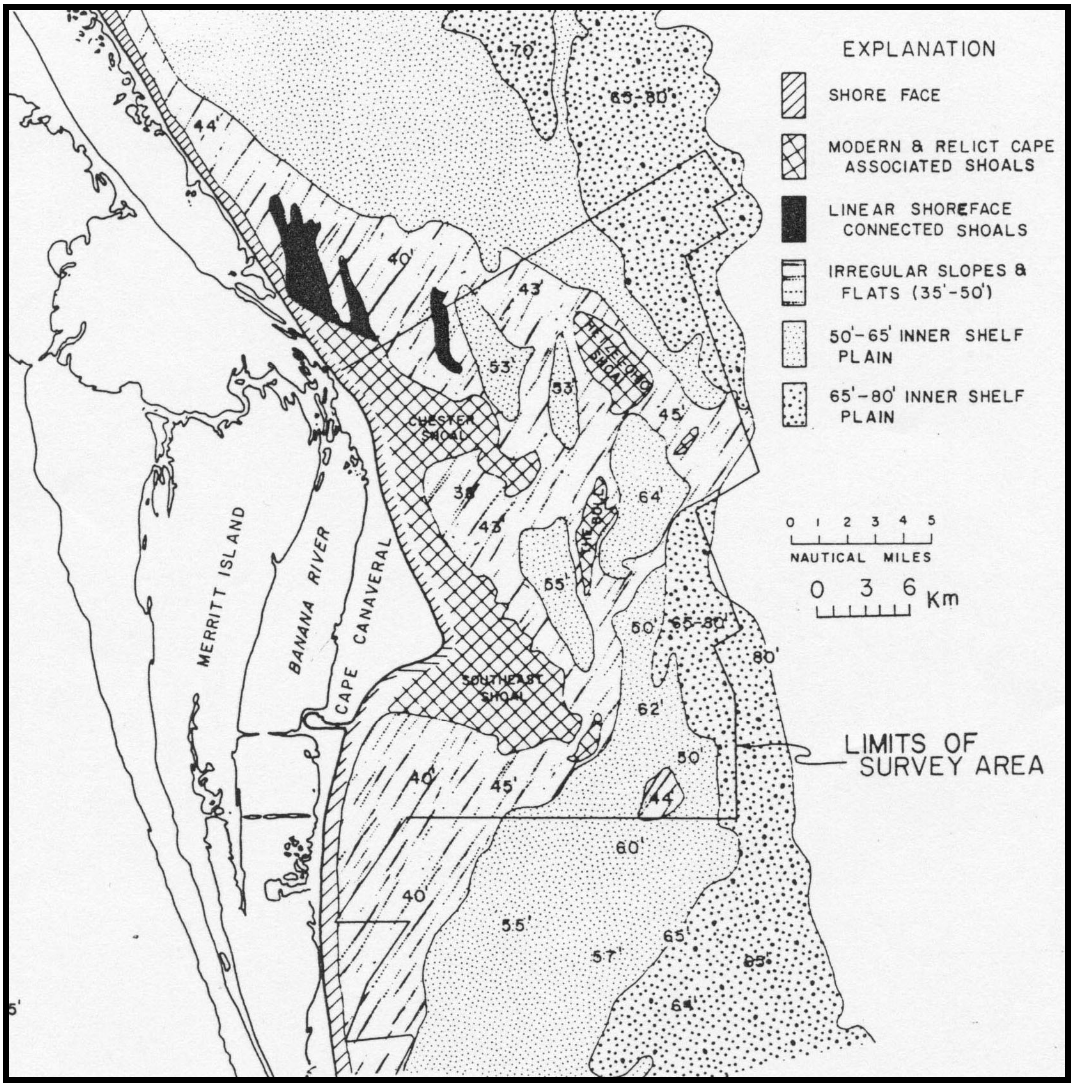

Figure 2-7. Morphological subdivisions of the Cape Canaveral Inner Continental Shelf. Soundings are from National Ocean Survey Chart 1245 (from Field and Duane, 1974).

Morphologic features on the Inner Shelf Plain consist of a series of platforms or step-like flats, gentle slopes leading from one flat to the next, and shoals (Meisburger and Duane, 1971). Inner Shelf Plain deposits contain considerable variation from north to south due to shoal morphology. Shoals within the northern extent of the study area are abundant and large, including cape-associated shoals trending southeast from Cape Canaveral and large isolated linear shoals immediately seaward of the shoal tips (Meisburger and Duane, 1971). Consolidated and unconsolidated ridges have been identified by previous investigations within this region. Consolidated ridges may represent former strandline deposits on the shelf edge. Large shoals, ridges, and channels exist along the shelf surface adjacent to the Cape from the shoreface to about 12 km offshore. The alignment of ridges parallels the cape shoreline and extends southeast from the foreland. The shoal system extending southeast from Cape Canaveral generally is very shallow, with depths ranging from about 4 to 12 m. Shoreface-attached shoals and the cape shoals are actively changing in configuration by modern nearshore processes. Analysis of shoal migration in this region shows them to be broadening and thickening (USACE, 1999a) and migrating to the south

(Byrnes and Kraus, 1999). Direct evidence of active reworking is recorded by sediment characteristics and bathymetric data (Field and Duane, 1974; Byrnes and Kraus, 1999).

South of Cape Canaveral, the Inner Shelf Plain is characterized by a gentle seaward inclination, a narrow depth range, and a general alignment parallel to the northwesterly trend of the shoreline. Between Port Canaveral and Sebastian Inlet, the inner shelf is lacking the variable shoal topography found to the north and south. South of Sebastian Inlet, shelf topography again becomes more complex. Shoal characteristics in this region have been well-studied and summarized by Duane et al. (1972) and Meisburger and Duane (1971). The southern shoal complex contains numerous shoreface-attached and isolated linear shoals with their long-axes lying predominantly north-south. Nearly all shoals are linear and have a north or northeasterly alignment, except for Thomas Shoal off Sebastian Inlet and an unnamed ridge between St. Lucie and Capron Shoals. These two shoals have a northwesterly alignment suggesting a different genetic process or time of formation. Most shoals in the study area are located about 12 to 14 km offshore, landward of the 20-m depth contour, and range in depth from about 8 to 14 m. Bethel Shoal is located further offshore, at a distance of about 18 km. Shoals tend to crest at about -6 to -10 m, with some of the smaller shoals cresting at about -15 m. Shoal profiles illustrate a smooth and regular surface, with symmetrical and asymmetrical cross-sectional form (Figure 2-8). Where asymmetry exists, the steeper flanks face southeast. Sediments comprising the shoals typically are well sorted biogenic medium- to coarse-grained sand with 15% to 30% quartz. Between the shoals, the seafloor is nearly flat and is covered by a layer of biogenic sand similar to that comprising the shoals. However, the sand tends to be more poorly sorted, more angular, and is highly bored by encrusting organisms. Many shoals visible on the seafloor exist seaward of the Federal-State Boundary, creating ideal locations for potential sand borrow sites for beach nourishment.

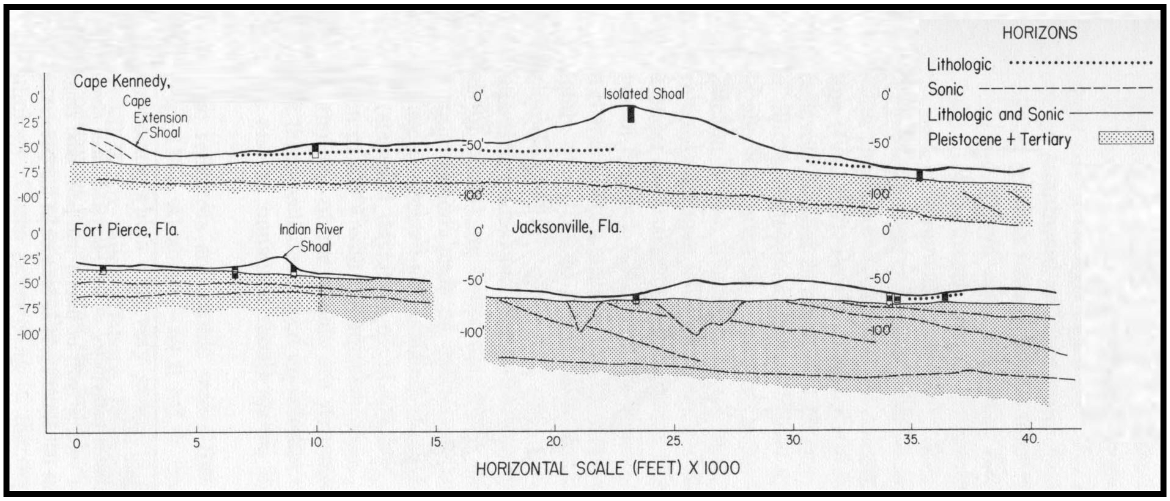

Figure 2-8. Shoal profiles offshore Cape Canaveral and Fort Pierce, FL (from Duane et al., 1972).

2.1.2 Surface Sediments

There is general agreement that surficial sediment on the shelf offshore central east Florida is composed primarily of well-sorted, medium-to-coarse quartzose calcareous sand that contains a high percentage of shell fragments (Meisburger and Duane, 1971; Field and Duane, 1974; Nocita et al., 1990; Amato, 1993). There are a number of sand rich areas along the shelf, with sand thicknesses generally related to shelf topography (thick under shoals and relatively thin under flats and swales) (Nocita et al., 1990). Sediment grain size generally increases to the south, with median grain size and the percentage of carbonate showing considerable variation from one area to the next. The increase in size and local variability are due to the presence of local coquina outcrops in this area. Field and Duane (1974) characterized surface sediment on the shelf adjacent to Cape Canaveral as well-sorted, medium-to-coarse quartzose calcareous sand that is presently being reworked and redistributed. They concluded that surficial sediment has been generated in part by biogenic activity and southerly littoral transport of eroded coastal materials, but that most sediment was derived from seafloor erosion of underlying Pleistocene deposits. Most erosion of the older weathered surface occurred during transgression, but physical and biological erosion are still active in some areas. At some locations, the Pleistocene surface crops out on the seafloor as ledges and rock surfaces (Field and Duane, 1974).

A study completed by Amato (1993) found that sand on the inner shelf north of Cape Canaveral locally contains up to 75% calcium carbonate, mostly in the form of shell debris (Figure 2-9). He concluded that sand was probably deposited by fluvial processes. Sand on the middle and outer shelf areas is mostly medium to coarse grained (Milliman, 1972). Amato (1993) estimated that at the Cape, shelf sand contains 25 to 50% carbonate that increases to greater than 75% southward and seaward. Nocita et al. (1990) completed a study of the area offshore Cape Canaveral for surface sediments and potential sand thicknesses. He concluded that offshore sand-rich areas roughly corresponded to shoal areas, and that virtually all of Southeast Shoal, with water depths greater than 10 m, was greater than 90% sand (Figure 2-10). Chester Shoal, the shore-attached shoal to the north of the Cape, as well as several isolated offshore shoals, were also sand-rich (Nocita et al., 1990). This study found that the gravel-rich areas were greatest in areas closest to shore north of Cape Canaveral, and that the only areas with significant amounts of mud-rich sediments were located south of Southeast Shoal (Figure 2-6). The USACE (1999a) collected sediment samples along Southeast Shoal within Sand Resource Area A1 and found that the median grain size of sediments ranged from 0.18 to 0.56 mm, for an average of 0.55 mm. Shell content in collected samples ranged from 34 to 53%, for an average of 43%.

Meisburger and Duane (1971) found that the dominant sediment type south of Cape Canaveral was primarily medium to very coarse, poorly sorted calcareous sand. Quartz was present, but its content ranged widely from a few percent to over 40%. Quartz sand occurs as a ubiquitous blanket over the inner shelf, covering low relief areas to about 1.5 m thick, with greater thickness over shoals. Deposit thickness ranged from a 0.5 to 5.0 m, with sand thickness exceeding 10 m in some areas. Meisburger and Duane (1971) attributed the source of most sediment particles found in cores offshore Fort Pierce to benthic biota. Quartz, the only noncarbonate particle present in significant quantity, was derived from the Piedmont Province because no primary quartz-bearing rocks crop out along the Florida Peninsula. Meisburger and Duane (1971) postulated that the origin of carbonate sediments in this region was from local shelled organisms or may have originated outside the area and subsequently entered as detrital sediments. A third possibility is that the skeletal fragments were reworked from older, underlying formations (Meisburger and Duane, 1971). Sediments of the Anastasia Formation are composed of a highly variable series of coquina, sand, and biogenic limestone deposits possibly representing depositional episodes throughout the Pleistocene (Meisburger and Duane, 1971).

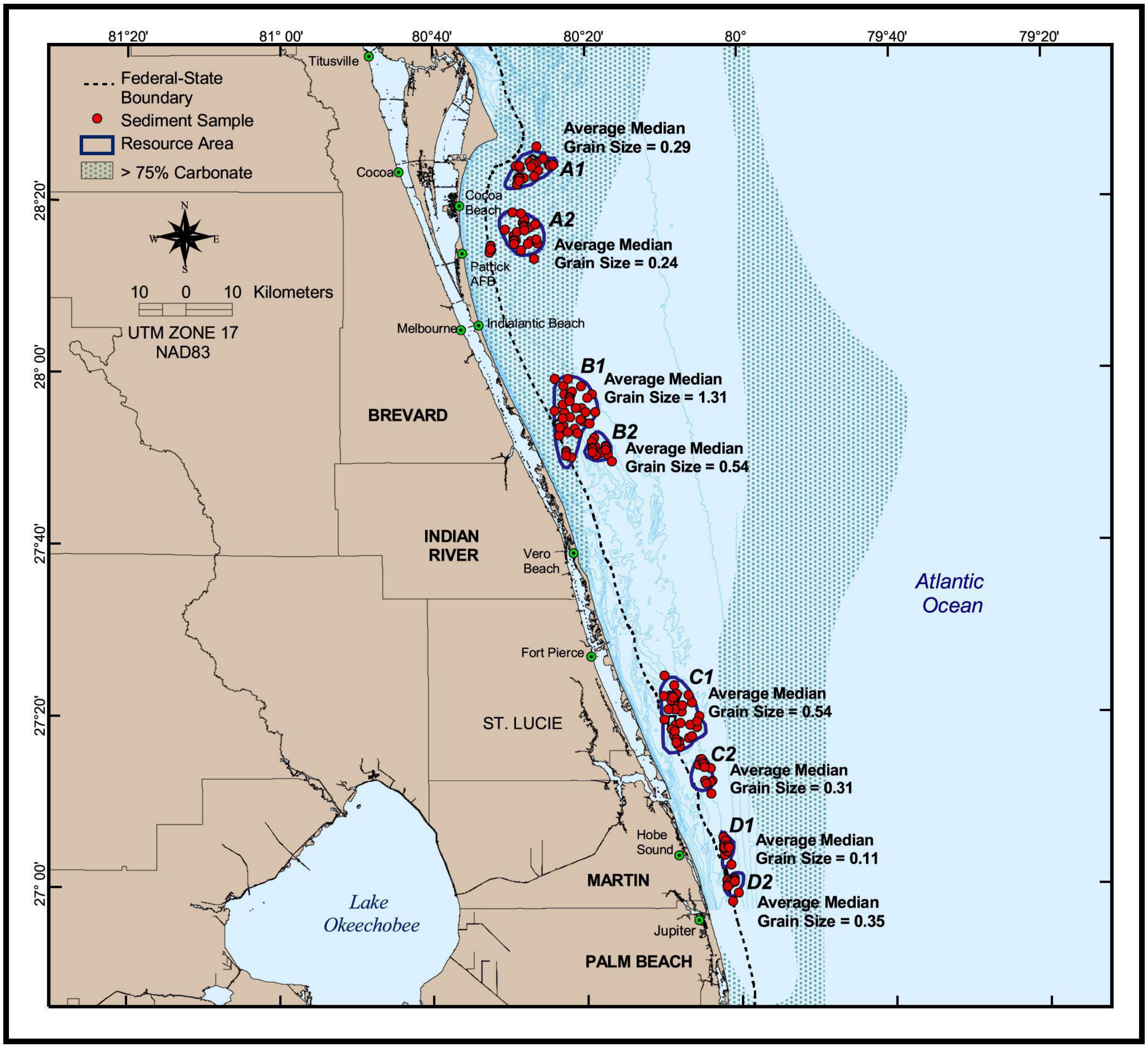

Figure 2-9. Sediment grab samples collected offshore central east Florida.

Grab samples were collected at each of the sand resource areas to provide additional information on surface sediment characteristics. Sample locations and average median grain size for each site are illustrated in Figure 2-9, along with areas determined by Amato (1993) as consisting of greater than 75% carbonate. Overall, the sediment distribution displayed by these samples was consistent with trends observed by previous investigators. The predominant sediment type found within the resource areas is medium- to coarse-grained sand, with five of the nine resource areas (A1, B2, C1, C2, and D2) indicating an average median grain size within either of these two categories. Four of these five resource areas contain proposed borrow sites. Each of these is located on sand shoals, consistent with sediment characterizations made by Duane et al. (1972) for shoal sedimentary composition.

Resource Areas A2 and D1 had the smallest average grain size, classifying these two regions as fine sand and very fine sand, respectively. Area D1 is classified as very fine sand (0.11 mm) and is located in the deepest water of all sand resource areas. Area A2 is classified as fine sand (0.24 mm) and is located within the gently sloping Inner Shelf Plain, lacking variable topography that tends to dominate other sand resource areas. Resource Area B1 has the largest median grain size (1.31 mm), classified as very coarse sand. The location of Area B1, offshore Sebastian Inlet, is within an area that has been defined by McLaren and Hill (2002) as consisting of a high percentage of carbonate. Although average median grain size for this resource area is larger than that calculated for borrow sites in other areas, sediment samples obtained within and immediately adjacent to the borrow site in Area B1 have an average median grain size of 0.6 mm. Overall, sediment size distribution illustrated by surface sediment samples demonstrated the dominance of medium- to coarse-grained sand along the central east Florida continental shelf, particularly associated with offshore shoals.

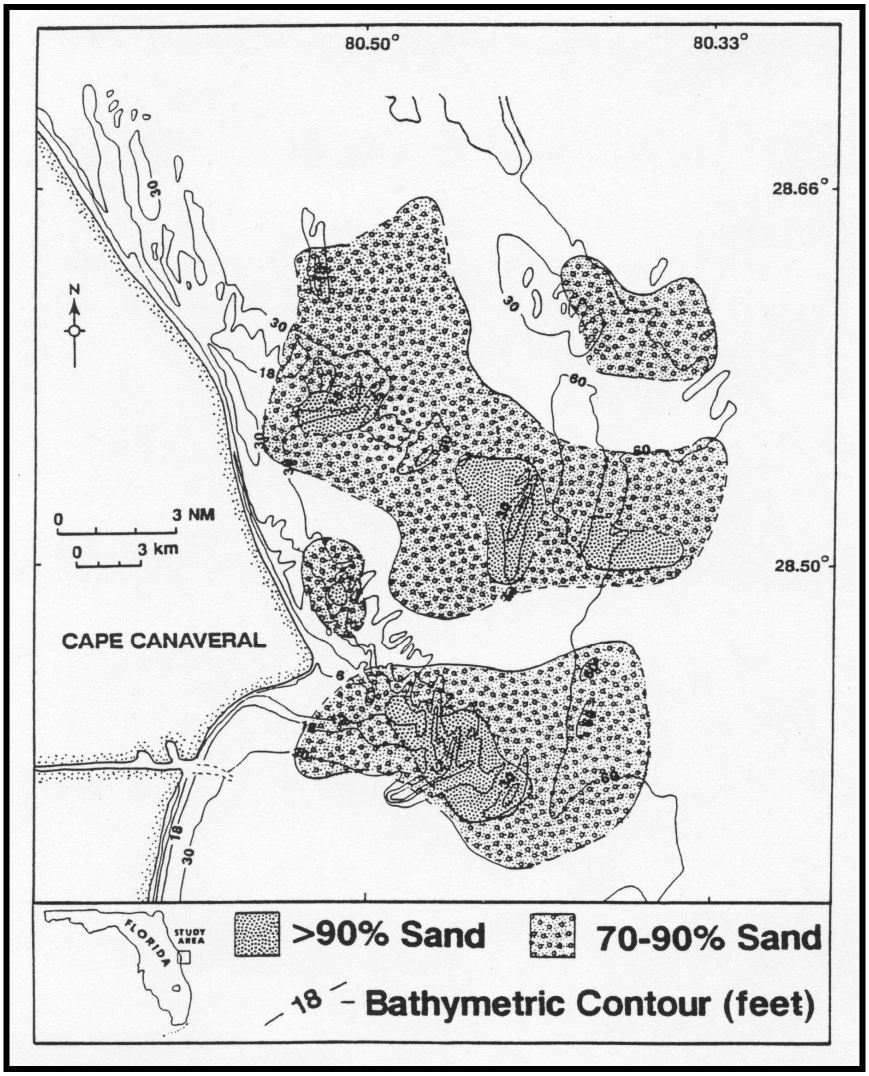

Figure 2-10. Distribution of sand-rich sediment in upper portion of shoals seaward of Cape Canaveral (from Nocita et al., 1990).

2.1.3 Subsurface Deposits

Numerous geological studies have been conducted within the study area to document continental shelf sedimentation processes and describe the regional character of shelf stratigraphy and sedimentology. Early investigations completed by the ICONS program

(Meisburger and Duane, 1971; Field and Duane, 1974) developed regional subsurface geological characterizations of the continental shelf adjacent to Cape Canaveral and offshore southern Brevard, Indian River, St. Lucie, and Martin Counties. Much of the work completed between southern Brevard and Martin counties was focused on the area adjacent to Fort Pierce Inlet. Recent studies completed by the FGS have built upon this early work and provided further detailed depictions of surficial and subsurface geology along the Florida Continental Shelf. The USACE (1999a) examined surface and subsurface sediments at Southeast Shoal within the borrow site in Area A1 to determined potential sediment thicknesses. Additionally, Duane et al. (1972) documented the shallow geology of nearshore and offshore sand ridges for determining the genesis of shoreface ridge deposits.

Field and Duane (1974) examined the geomorphology and sediment characteristics in the region offshore Cape Canaveral by collecting vibracores and high-resolution seismic data. The extent covered by seismic profiling generally fell outside the major offshore shoal seaward of the Cape. Nocita et al. (1990) designed an investigation of shore-attached shoals seaward of the Cape. The study included collecting surface sediment samples, vibracores, and seismic reflection profiles. Two sets of sediment samples, including a total of 84 vibracores and 140 surface samples, in addition to 174 km of seismic profiles, were collected to document the distribution of surface and subsurface sediments, especially those which might be desirable for the purposes of beach nourishment. Surface and subsurface sedimentary characteristics were determined and lateral extents and subsurface thicknesses of sand deposits on the shoals were estimated.

Shelf sedimentary deposits offshore Brevard to Palm Beach counties were evaluated by Meisburger and Duane (1971). The study primarily focused on the offshore area adjacent to Fort Pierce Inlet, but included an extensive section of the inner shelf using seismic reflection data. Seismic lines were very widely spaced and were used to determine the subsurface character on a regional scale. The study focused on determining suitable offshore sites for obtaining beach nourishment material and determined sand resource thicknesses at particular shoals.

An on-going multi-year cooperative study between the FGS and MMS has collected and analyzed surface and subsurface sediments offshore southern Brevard, Indian River, St. Lucie, and Martin counties to identify and characterize offshore sand deposits suitable for potential beach restoration efforts along adjacent beaches. As part of this effort, push cores, grab samples, subsurface acoustic profiles, and vibracores have been collected at beach and offshore sites. Results obtained to date have provided most of the subsurface data relevant to characterizing the sedimentary characteristics of offshore sand resource areas.

2.1.4 Sand Resource Areas

The resource potential of offshore sand deposits within the study area was documented using geological data from Meisburger and Duane (1971), Duane et al. (1972), Field and Duane (1974), Nocita et al. (1990), the USACE (1999a), and Freedenberg et al. (1995b, 1997, 1999, 2000b). Sand volume estimates for Resource Area A1 were determined by Field and Duane (1974), Nocita et al. (1990), and the USACE (1999a). Nocita et al. (1990) concluded that at least 3 m of suitable beach nourishment material is available across a wide area of the shoals. Freedenberg et al. (2000b) documented that appreciable amounts of sediment were available within Southeast Shoal (Figure 2-11). Vibracores collected along the southwest flank of Southeast Shoal, an extension of the

Canaveral Shoal deposit, recorded more than 90% sand-sized material for most of the feature (Nocita et al., 1990). Sand thicknesses obtained from cores indicated that about 6 m of suitable material was available across Southeast Shoal. A study completed by the USACE (1999a) collected 30 vibracores within the borrow site associated with Area A1. Sediment analysis indicated that the beach-quality sand deposit associated with the borrow site in this area was a minimum of 3 m thick and was greater than 4.5 m at most core locations. The sand is coarse relative to local beach sand and contains a significant shell fraction.

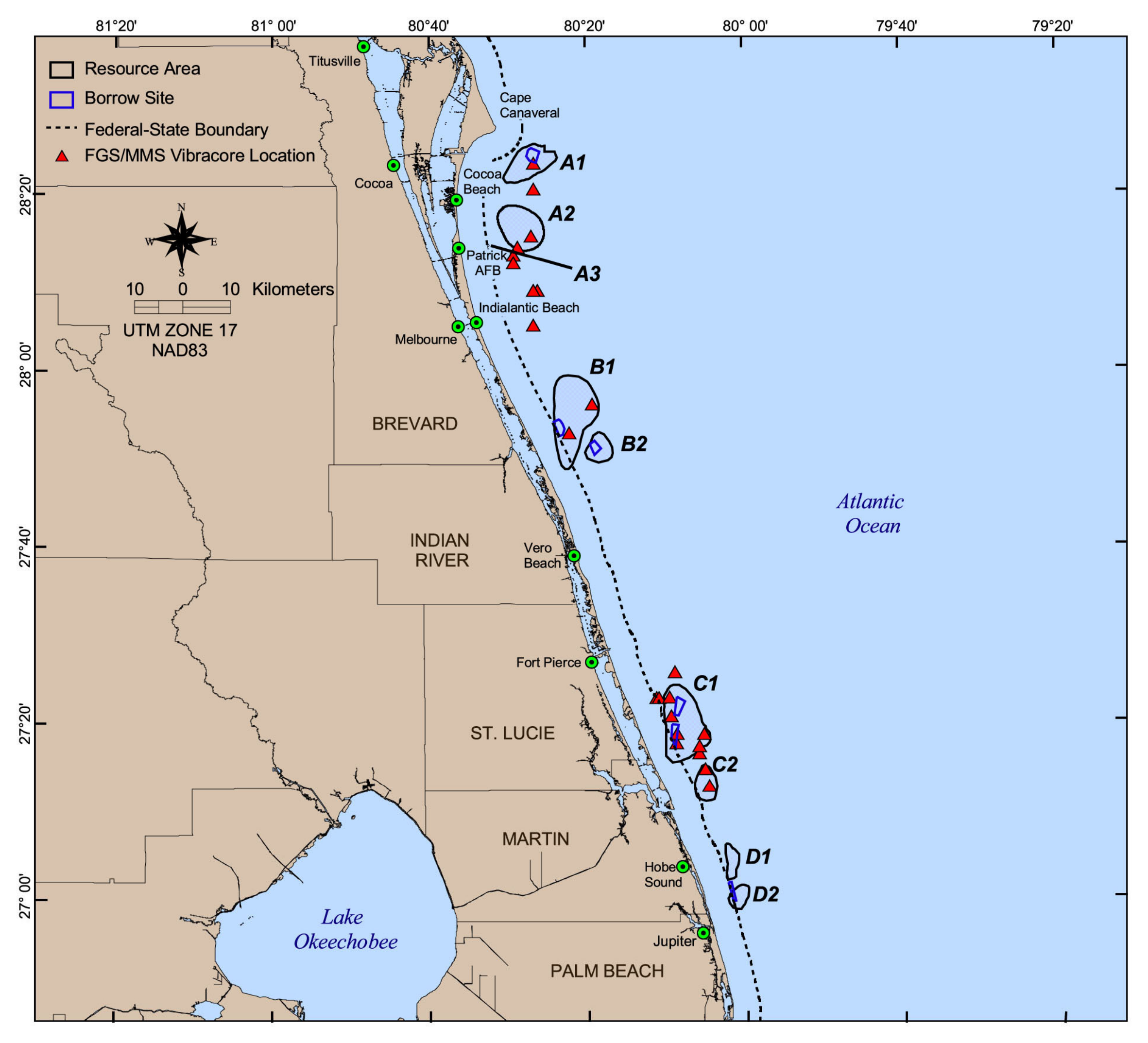

Figure 2-11. Vibracore locations offshore central east Florida (data from Freedenberg et al., 1999).

Sand resource areas situated to the south of Cape Canaveral are all located on or adjacent to linear sand shoals (Figure 2-11). Sand shoals within this area were identified by Meisburger and Duane (1971) as containing large quantities of suitable sediment for beach nourishment. Potential sand thickness estimates at Areas B1 and B2 were determined using vibracore data collected by the FGS and MMS. Two vibracores, VB-9 and VB-10 were collected along the flank of Thomas Shoal, and contained about 2 and 2.5 m of beach-quality restoration sand, respectively (Freedenberg et al., 1999). Both vibracores were collected within Area B1, which lies on the flank of the shoal and has a potential borrow site located immediately adjacent to the Federal-State boundary. The borrow site in Area B2 is located along the crest of the Thomas Shoal.

Sand volume estimates at Resource Areas C1 and C2 were determined using vibracore data collected by the FGS and MMS. Six vibracores were sampled within these areas with sediment thicknesses ranging from 3 and 7 m. Only Area C1 has potential borrow sites located along the crest of St. Lucie Shoal and defined as C1 north and C1 south. Two of the four vibracores from Area C1 were collected directly within Borrow Site C1 south, indicating 6 to 7 m of suitable sediment. Area C2, located along the northern flank of Gilbert Shoal, was characterized using two vibracores. Each core showed suitable sediment thicknesses of about 2 m.

Resource Areas D1 and D2 have not been characterized to date as part of the FGS/MMS cooperative agreement. Only Area D2 has been assigned a potential borrow site. Characteristics of this borrow site, including its location along a small ridge crest and the median grain size of 0.35 mm for surface sediments, indicated that it had good potential as a suitable borrow site. Relief of the shoal above the ambient shelf surface was used to define the thickness of sediment available for beach fill.

2.2 GENERAL CIRCULATION

Florida Current dominates circulation along the central east Florida continental shelf. However, wind-driven currents also play an important role. Unlike other shelf regions where density and tidal forces contribute substantially to circulation processes, the controlling parameter in the Florida Current area seems to be the lateral position of the frontal zone relative to the shelf; the closer the front, the greater the influence on local circulation.

The Florida Current is the local manifestation of the Gulf Stream, the intense western boundary current of the North Atlantic that transports heat north from the equator. The system narrows and intensifies between the southeast Florida shore and the Bahamas; this portion of the Gulf Stream is commonly known as the Florida Current. The axis of the Florida Current runs northward, east of the study area. Flow speeds can exceed 2.5 m/sec (Lee et al., 1985).

Circulation processes within the study area include spin-off eddies and meanders of the Florida Current, wind-driven currents, upwelling/downwelling dynamics, and tides. Other contributions may stem from shelf waves, inertial oscillations, and coastal inlet exchange. Shelf currents are aligned principally along isobaths; cross-shelf components are typically much weaker. Despite the presence of multiple forcing mechanisms, most current energy on the shelf can be related to subtidal variability (Lee and Mayer, 1977). The position of the Florida Current front is the principal control of subtidal shelf circulation from Miami to Cape Hatteras (Zantopp et al., 1987).

2.2.1 Florida Current and Eddies

The Florida Current frontal zone meanders laterally along the shelf break. Meanders can be caused by instability of the Florida Current, instabilities caused by topographic features, and variable wind stress that pushes the Florida Current axis onshore and offshore (Lee and Mayer, 1977). Meanders travel northward as waves; wave crests are onshore excursions of the front and troughs are offshore excursions (Zantopp et al., 1987). Horizontal velocity shear between the Florida Current and ambient shelf waters produces cyclonic 'spin-off' eddies along the western edge (Lee, 1975). Once formed, these eddies propagate northward along the shelf. Eddies have length scales of approximately 10 km in the east-west direction and 20 to 30 km in the north-south direction. Eddies form consistently, about once every 2 days to 2 weeks, depending on location and time of year (Lee, 1975; Lee and Mayer, 1977; Lee and Mooers, 1977; Lee and Atkinson, 1983; Santos et al., 1990). Spin-off eddies translate northward at speeds about 20 to 100 cm/sec (Lee and Mayer, 1977). Zantopp et al. (1987) tracked three eddies in summer of 1984 and reported translation speeds of 40 to 60 cm/sec. Swirl speeds within the eddy can be 100 cm/sec to the north and 50 cm/sec to the south (Lee and Mayer, 1977).

Eddies penetrate occasionally onto the inner shelf (depths less than 20 m). North of Cape Canaveral, where the shelf is relatively broad, Santos et al. (1990) showed that Gulf Stream effects were negligible at the 28-m isobath. Wind stress along the shelf dominated subtidal currents in the nearshore region. Gulf Stream effects became more pronounced at the 40-m isobath and dominated currents at the shelf break (75-m isobath). Lemming (1980) reported inner shelf currents at locations north of Cape Canaveral were highly consistent with winds. At Miami, where the shelf is quite narrow, Lee and Mayer (1977) found flow on the inner shelf markedly different than the outer shelf. At depths less than 10 m, inner shelf currents responded directly to wind stress, either northward or southward depending on wind direction, while variability on the outer shelf was due to eddy and Florida Current meander effects. Smith (1981) found that current variability on the narrow inner shelf (depths <10 m) near Fort Pierce was poorly correlated to wind stress, suggesting observed variability was likely a dynamic adjustment to Florida Current eddy intrusions.

Eddies also are important drivers of water mass exchange along the shelf, triggering upwelling events along the shelf throughout the year. Smith (1981, 1982, 1987) and Lee and Pietrafesa (1987) show intrusions of cooler water onto the shelf were inconsistent with Ekman-type wind stress, where winds push surface waters offshore and colder bottom waters upwell toward shore in response to a pressure deficit near shore. Rather, temperature and current variability were more consistent with eddy intrusion. Hsueh and O'Brien (1971) described how frictional forces between a steady alongshore current and the shelf create a cross-shore geostrophic imbalance, inducing onshore bottom flow, or upwelling. Colder waters, beneath the Florida Current, upwell and become entrained in spin-off eddies. The cyclonic eddies then mix horizontally with warmer Florida Current waters, especially on the leading edge of the meander, forming elongated filaments and shingles of the Florida Current along the shelf (Zantopp et al., 1987). Such mechanisms explain observed temperature and density variability within the study area as well as the important role eddies play as nutrient suppliers to coastal waters (Lee et al., 1991). Freshwater inputs, such as river runoff, have negligible impact on density along the Florida shelf (Lee and Pietrafesa, 1987).

2.2.2 Wind-Driven Currents and Upwelling

Seasonal wind variations contribute to shelf circulation indirectly by enhancing or repressing eddy-induced upwelling. From October to March, prevailing northeasterly winds create an onshore Ekman response and associated downwelling. Bottom currents oppose upwelling induced by Florida Current eddies. Hence, winter upwelling events are not as prolonged as during other months when predominant southeast winds create upwelling-favorable conditions, enhancing eddy-induced effects. Summer upwelling events can last for several weeks (Smith, 1983, 1987). Lee and Pietrafesa (1987) suggest that southwest winds drive localized upwelling due to the anomalous topographical feature at

Cape Canaveral. On the inner shelf, wind-driven subtidal variability also would be expected to have seasonal responses; winter conditions (northeast winds) would drive a southerly flow and summer conditions (southeast winds) would favor northerly currents.

2.2.3 Tidal Currents

Mayer et al. (1984) analyzed recent observations of the Florida Current around 27° latitude, and they reported tidal currents were responsible for approximately 16% of the total Florida Current variability. Diurnal tides were stronger than semi-diurnal tides, accounting for as much as 80% of the tidal energy. Peak tidal current speeds in water deeper than 300 m were about 12 cm/sec. Mayer et al. (1984) also suggested tidal oscillations were greatest on the western edge of the Florida Current. Lee and Mooers (1977) reported tides accounted for 10% to 25% of the Florida Current variability on the 300 m deep Miami Terrace area. Kielmann and Duing (1974) analyzed a 50-day record obtained offshore of Miami in about 300 m water depth, and tides accounted for about 25% of the along-axis current; diurnal components dominated. Cross-axis tides contained about 6% of the overall variance, again dominated by the diurnal constituent.

Extant literature provides less information on shelf tides within the study area. However, Smith (1982) measured oscillating tidal currents along the inner shelf off Fort Pierce at speeds approximately 10 cm/sec at the bottom. Cross-shelf tidal components rarely exceeded 10 cm/sec.

2.2.4 Storm-Generated Currents

Smith (1982) also described the response of shelf waters to Hurricane David (1979) based on near-bottom observations collected in 10 m water depth offshore Fort Pierce. Storm effects were characterized as a brief 1 m rise above normal high water, a doubling of peak current speeds along shore, and a marked decrease in bottom temperatures. Current speeds exceeded 60 cm/sec during the event compared to typical peak speeds of 30 cm/sec. Cross-shelf currents reached 30 cm/sec versus more typical speeds of 15 cm/sec. Near-surface currents at mid-shelf (depth ~26 m) measured 80 cm/sec versus typical peak currents of 40 cm/sec in the alongshore direction. Peak wind gusts during the event measured about 75 knots in southern Florida (National Hurricane Center archives).

2.2.5 Waves and Wave-Generated Currents

Wave height, period, and direction of approach, in addition to the magnitude and phasing of storm surge, are the most important dynamic factors influencing beach change in central east Florida. In most cases, buoy data are the preferred source of wave information because they represent actual measurements rather than hindcast information derived from large-scale models. However, very few sites along the U.S. east coast have wave measurement records of sufficient length to justify their use as a source of long-term information. McBride (1987) summarizes variations in wave height for the east coast of Florida using various USACE reports (Figure 2-12). Offshore central east Florida, sources of measured directional wave data include the Florida Coastal Data Network (CDN) (Wang et al., 1990) and various short-term deployments of individual gages (e.g., the 1991 University of Florida deployment of a wave gage offshore Jupiter Island [Harris, 1991]). However, the most comprehensive analysis of nearshore wave climate for central east Florida is by the USACE, Coastal and Hydraulics Laboratory, through wave hindcast studies (Hubertz et al., 1993). A description of nearshore wave characteristics at four USACE Wave Information Study (WIS) stations offshore the study area is presented in Section 4.1.1.1.

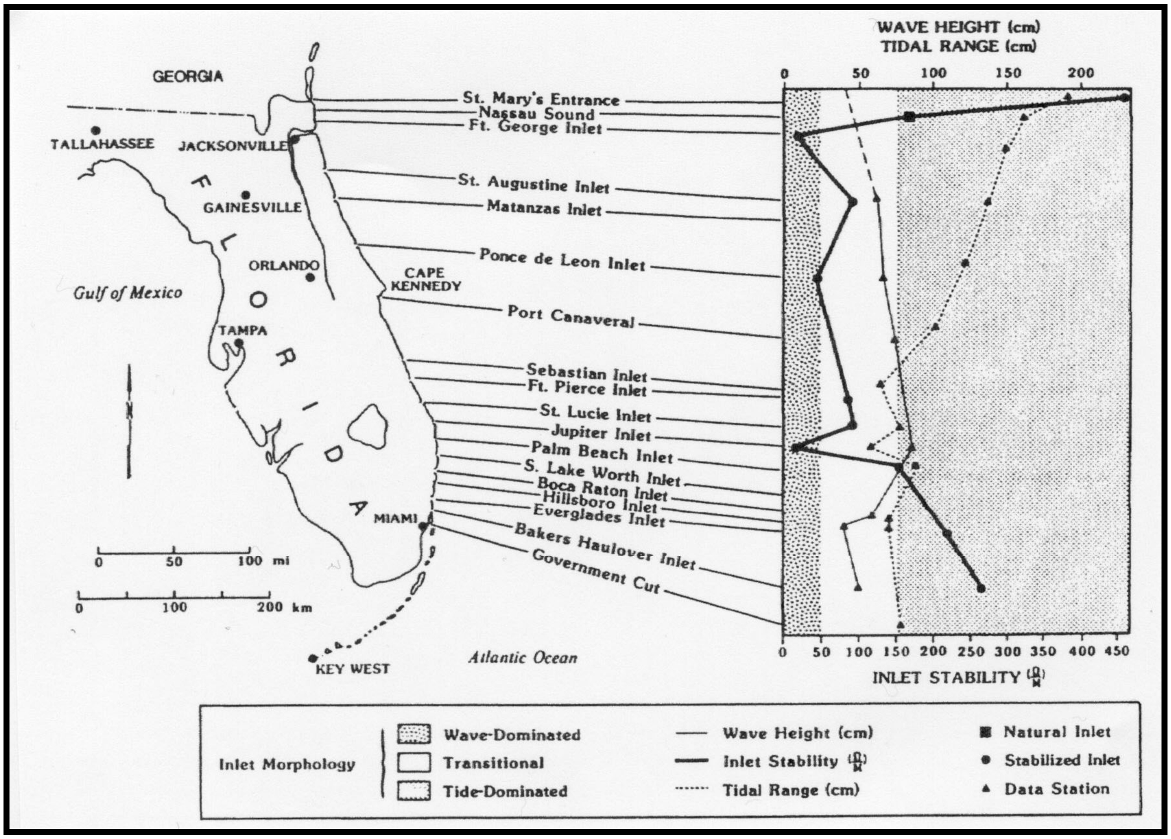

Figure 2-12. Plot of tidal range and wave height for the east coast of Florida (from McBride, 1987).

2.2.6 Nearshore Sediment Transport

As illustrated in Section 4.1.1.1, waves offshore central east Florida propagate principally from the east and northeast, producing net southerly transport of sand on beaches and in the nearshore (Duane et al., 1972; McBride, 1987; Dean, 1988; USACE, 1996). As illustrated in Figure 2-13, estimated net longshore sand transport along the east coast of Florida is quite variable, decreasing from approximately 600,000 yd^3/yr at Fernandina to about 10,000 yd^3/yr at Miami (Dean, 1988). Within the central east Florida study area, net southerly littoral drift is estimated at 350,000 yd^3/yr near Cape Canaveral (USACE, 1967, 1996; Kraus et al., 1999), decreasing to about 230,000 yd^3/yr at Jupiter Inlet (Duane et al., 1972; Dean, 1988). Substantial variations in estimated net longshore sand transport exist within this area as a function of dominant wave approach angle and shoreline orientation. Changes are illustrated by potential transport estimates computed for each wave modeling grid in Section 4.2.2 and historical shoreline change trends in Section 3.1.3.

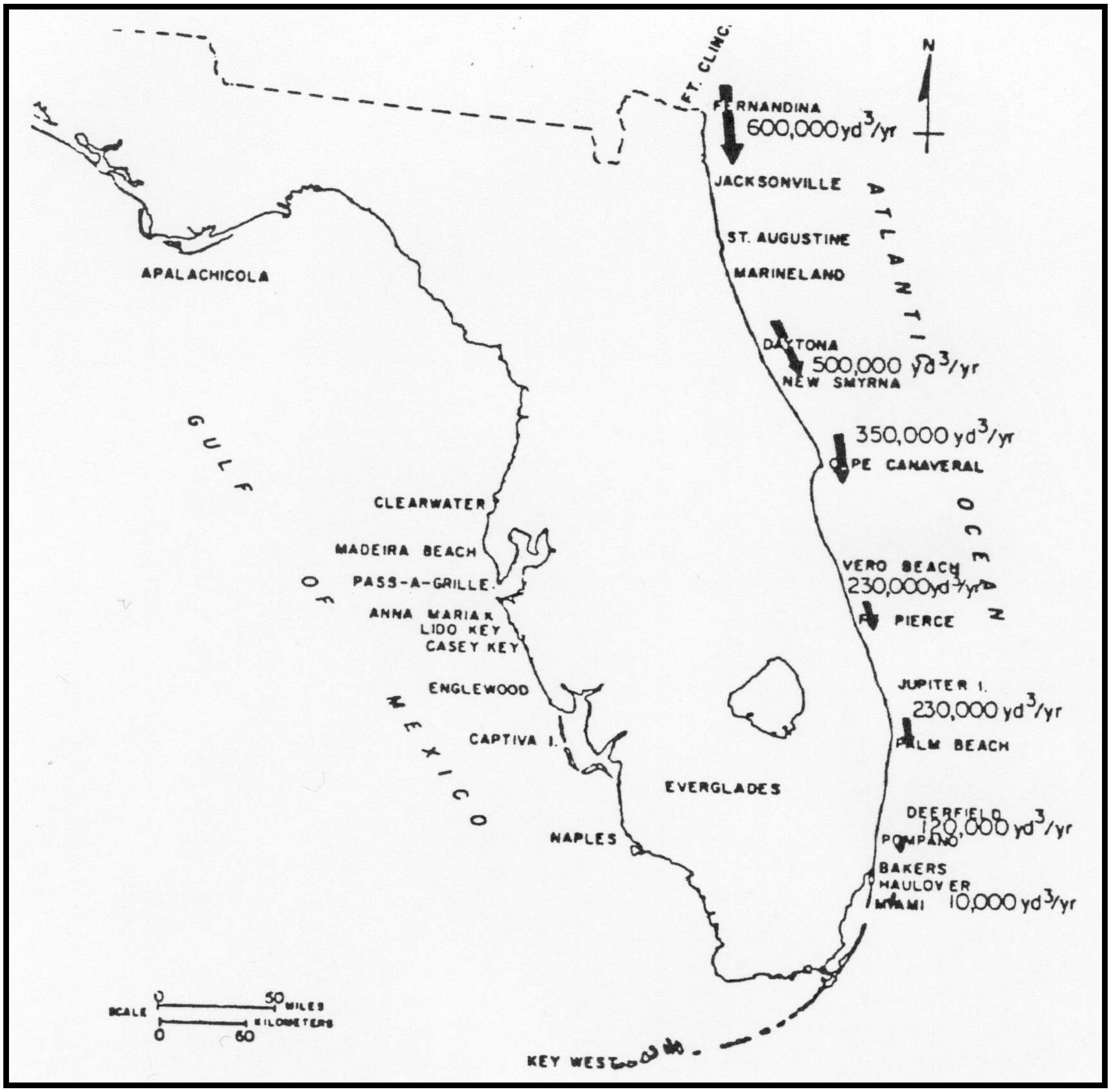

Figure 2-13. Estimates of net annual longshore sand transport along the east coast of Florida derived primarily from USACE documents (from Dean and O'Brien, 1987; Dean, 1988).

2.3 BIOLOGY

2.3.1 Benthic Environment

2.3.1.1 Soft Bottom

Infauna

Infaunal organisms inhabiting inner shelf waters offshore central east Florida predominantly consist of members of the major invertebrate groups that commonly inhabit sand bottom marine ecosystems, including crustaceans, echinoderms, mollusks, and polychaetous annelids. Infaunal assemblages that inhabit shelf waters of the study area include taxa common to much of the South Atlantic Bight (SAB) (Tenore, 1985; Weston, 1988; Barry A. Vittor & Associates, Inc., 1991, 2000), eastern Gulf of Mexico (Dames & Moore, 1979), and tropical areas of southern Florida and the Caribbean (Foster, 1971;

Camp et al., 1998). Generally, inner shelf infaunal assemblages are numerically dominated by polychaetes in terms of overall abundance and taxa (Day et al., 1971; Tenore, 1985; Weston, 1988; Barry A. Vittor & Associates, Inc., 1990, 1991, 2000). Other conspicuous members of the coastal infaunal community include amphipod crustaceans and bivalve mollusks. Infauna that inhabit sand bottoms in the study area are similar to marine assemblages in other regions in that they comprise assemblages that exhibit spatial and seasonal variability in their distributions.

East coast Florida waters are a transitional area between major zoogeographic zones. Macrofaunal assemblages inhabiting shelf sediments of the study area include a mixture of warm-temperate Carolinian and tropical Caribbean Province fauna (Briggs, 1974; Lyons, 1989), in addition to a significant endemic component (Camp et al., 1998). Several areas of the continental shelf along the southeastern U.S. have been suggested as transitions between temperate and tropical fauna, although areas of the Florida east coast have been proposed most often (Briggs, 1974). Briggs (1974) reviewed studies of species distributions along the U.S. east coast and determined that, based mostly on distributional data reported by others, the geographic location of a temperate/tropical faunal boundary is poorly defined, but that Cape Canaveral seemed to be centrally located within a broad north-south transition zone. However, Tenore (1985) found no latitudinal gradient of infaunal assemblage change on the inner continental shelf over a wide area of the SAB between Cape Fear, North Carolina and Daytona Beach, Florida, suggesting an absence of a geographically persistent transition area between faunal provinces across the region.

The extent of tropical fauna intrusion into more northerly latitudes is due primarily to the Gulf Stream (also referred to as the Florida Current), which brings warm water northward (Briggs, 1974). Convergence of biogeographic provinces in the region of Cape Canaveral largely is a result of interaction between various ocean currents that determine the latitudinal extent of relatively cool or warm water temperatures, creating an ecological barrier for members of the respective province assemblages. According to Lyons (1989), the Cape Canaveral area is characterized by the occurrence of tropical assemblages more than 40 km offshore, where the Gulf Stream flows, whereas much of the inshore fauna is associated with the warm temperate Carolinian Province. In the southern portion of the study area, near Jupiter Inlet, the inner edge of the Gulf Stream is usually less than 10 km offshore. In this area, for example, there is a marked increase of tropical mollusks on the inner shelf (Lyons, 1989).

Many of the most abundant infauna in the study area are among the numerical dominants across a broader geographic area. Tenore (1985) found that polychaetes were numerical dominants over a wide area of the SAB, accounting for over half of the total overall abundance. There was no obvious numerical dominance of any taxon that persisted seasonally in the SAB. Of the most abundant species, only 18 taxa comprised more than 0.2% of the total infaunal density at all stations in at least one season for the SAB study, including but not limited to the polychaetes *Spiophanes bombyx*, *Parapionosyllis longicirrata*, *Spio pettiboneae*, *Exogone lourei*, *Prionospio cristata*, *Protodorvillea kefersteini*, and *Goniadides carolinae*, and the cumacean *Oxyurostylis smithi*. Many of these numerically dominant taxa also are common in the Caribbean, for example, the polychaetes *S. bombyx*, *S. pettiboneae*, and *P. cristata* (Foster, 1971). Offshore Hutchinson Island, Florida, in the southern part of the study area, Lyons (1989) found that most mollusks collected from inner shelf sediments are broadly ranging, eurythermal species that occur from Cape Hatteras, North Carolina to Brazil.

Relatively few open shelf benthic studies have been conducted in the study area. The Canaveral Harbor Ocean Dredged Material Disposal Site (ODMDS) was investigated during June 1990 as part of a monitoring study of that site (Barry A. Vittor & Associates, Inc., 1991). Benthic samples were collected from 15 offshore stations at water depths of 12 to 18 m. Sand stations outside the ODMDS commonly yielded great abundances of the amphipod *Acanthohaustorius pansus*, archiannelid *Polygordius*, bivalve *Ervilia concentrica*, and polychaetes *Goniadides carolinae* and *Prionospio cristata*. More recently, the Fort Pierce ODMDS was investigated as part of a monitoring study (Barry A. Vittor & Associates, Inc., 2000). Three benthic monitoring stations were located within the ODMDS and nine stations were located just outside this area, ranging in depth from 12 to 16 m. Polychaetes were the most numerous organisms (37.8% of the total assemblage), followed by amphipod, decapod, and isopod crustaceans (29.4%), and gastropod (12.9%) and bivalve (10.2%) mollusks. Overall, the numerically dominant taxa were the polychaetes *Goniadides carolinae* (15.9% of the total number of individuals) and *Protodorvillea kefersteini* (7.0%), and non-identified oligochaetes (5.4%) and rhynchocoels (5.3%). Other taxa collected from all 12 stations included the arthropod *Maera caroliniana*, bivalves *Crassinella lunulata* and *Crassinella martinicensis*, polychaete *Heteropodarke formalis*, and gastropod *Caecum imbricatum* (Barry A. Vittor & Associates, Inc., 2000).

Infaunal populations that comprise open shelf benthic communities are affected by abiotic environmental parameters, resulting in both seasonal and spatial variability in their distribution and abundance. Shallow coastal waters are characterized by a variety of environments having great diurnal, seasonal, and annual fluctuations in their chemical, hydrographic, and physical properties. Distributions and abundances of benthic invertebrates are regulated at a basic level by these physical environmental forces.

Temporal variation in population abundance may be a result of response to proximal environmental variability or due ultimately to the life history patterns of individual species. Seasonality of macrobenthic assemblages inhabiting open shelf sediments has been noted in numerous investigations (e.g., Frankenberg and Leiper, 1977; Flint and Holland, 1980; Schaffner and Boesch, 1982; Weston, 1988; Byrnes et al., 1999). Patterns of seasonal reproductive periodicity in marine systems apparently are related to ambient climatic conditions, primarily temperature, for most marine invertebrates (Sastry, 1978). Reproduction is more or less continuous at deeper shelf depths (Warwick, 1980), where greater environmental stability promotes seasonal persistence of outer shelf infauna (Schaffner and Boesch, 1982). Camp et al. (1977) found a transient arthropod assemblage on the inner shelf offshore eastern Florida and suggested that the high rate of species turnover was at least partially due to the area being within the temperate-tropical transition zone.

An absence of temporal patterns of abundance for some macrobenthic species in many cases is related to reproductive strategies. Transitional infaunal species that do not emerge necessarily on a seasonal basis often colonize an area because of intermittent conditions that are favorable for reproduction. Opportunistic species generally are tolerant to fluxes within their environment, but more importantly they are early and successful primary colonists due to their reproductive capacity and dispersal ability (Grassle and Grassle, 1974). These species often undergo eruptive population peaks, depending on their adaptive ability to withstand varying environmental conditions, and can exploit an open niche while avoiding competitive interaction (Boesch, 1977). Because habitat availability often is the result of random perturbations of the environment, such as significant riverine outflow due to flooding, the appearance of these taxa often occurs in tandem with such episodes. For other, non-opportunistic species inhabiting marine soft sediments, a lack of temporal patterns of abundance may indicate simply that seasonal patterns of variability do not exist for these species (Pearce et al., 1976).

In addition to temporal differences in benthic assemblage composition, conspicuous spatial variability often is evident in the distributions of populations inhabiting open shelf sediments. Spatially variable environmental parameters such as hydrography, water depth, and sediment type influence benthic assemblage composition and the extent of numerical dominance of those assemblages by various infaunal populations.

Changes in infaunal assemblage composition along broad depth gradients have been noted in several studies of shelf ecosystems. 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, North Carolina and found four subtidal zones 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 present study. The most common taxa of the turbulent zone were best represented at the 20-m depth station (Day et al., 1971). Tenore (1985) and Harper (1991) both reported a transition between inner shelf and continental slope fauna of the SAB and northern Gulf of Mexico, respectively. An approximate depth of 37 m is thought to be a transition between the fauna of shallow coastal zones and those of intermediate and deeper shelf zones offshore Florida (Camp et al., 1998).

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 depth-related factors such as hydrology, sedimentary regime, and seasonality override any effects of sediment particle size and type on infaunal assemblages. 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 physical 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. Moreover, inner shelf waters generally are less depositional in nature than outer shelf or slope waters due to a dynamic current regime near the bottom, although shallow areas affected by estuarine outflow may experience episodic deposition of fine materials, which can influence benthic community structure.

Although some descriptions of depth-related differences in benthic assemblages have encompassed geographically broad areas (Day et al., 1971; Flint and Holland, 1980; Tenore, 1985), local variability in bathymetric relief can result in habitat heterogeneity within an area of relatively minor differences of absolute depth. Trough features, especially those that are bathymetrically abrupt, can dissipate current flow along the substratum surface, resulting in deposition of fine materials, including organic material. Presence of fine sediments and organics in bathymetric depressions can support benthic assemblages that are distinct from nearby areas without depressions (Boesch, 1972; Lyons, 1989; Barry A. Vittor & Associates, Inc., 1999).

Previous sampling efforts in open shelf waters have demonstrated the importance of sediment type in determining infaunal population densities. Wigley and Theroux (1981) summarized the relationship between sediment type and infaunal abundance. Coarse-grained sediments generally support the greatest numbers of infauna, while fine-grained sediments support the least. Amphipods are found in all sedimentary habitats, although 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 abundances are greater in sand and gravel bottoms than in silt-clay habitats (Wigley and Theroux, 1981).

Lyons (1989) found that mollusk species abundance and assemblage composition were related to sediment type in inner shelf waters offshore Hutchinson Island, Florida. He found four species-sediment groups: 1) hard-packed, fine to very fine sands supported relatively few species or individuals; 2) well-sorted, medium-grained sands at an offshore shoal supported relatively few species but yielded many specimens; 3) poorly sorted, coarse to very coarse sediments in an offshore trough feature yielded twice as many mollusk species as did shoal sediments, but the number of individuals was similar to that found on the shoal; and 4) poorly sorted trough sediments of shell, gravel, and mud supported more species and many more individuals than any of the other three sediment types (Lyons, 1989).

Not only do sediment particle size and type influence faunal densities, they have a strong effect on the species composition of benthic assemblages (Sanders, 1958; Young and Rhoads, 1971; Pearce et al., 1981; Weston, 1988; Chang et al., 1992; Byrnes et al., 1999). Although many infaunal species occur across a range of sediment types, most infaunal taxa tend to predominate in specific sedimentary habitats.

Infaunal assemblages are composed of taxa that are adapted to particular sedimentary habitats through differences in behavioral, morphological, physiological, and reproductive characteristics. During the Canaveral Harbor ODMDS study (Barry A. Vittor & Associates, Inc., 1991), sand stations outside the ODMDS commonly yielded great abundances of the amphipod *Acanthohaustorius* sp. H, archiannelid *Polygordius*, bivalve *Ervilia concentrica*, and polychaetes *Goniadides carolinae* and *Prionospio cristata*. This sand assemblage was different from a silty sand assemblage collected inside the ODMDS and was numerically dominated by deposit feeders, including the bivalves *Abra aequalis*, *Diplodonta semiaspera*, *Lucina multilineata*, *Mysella planulata*, and *Tellina versicolor*, and polychaetes *Scoletoma verrilli*, *Magelona* sp. H, and *Paraprionospio pinnata*.

Fine-textured sediments are generally characteristic of depositional environments, where occluded interstitial space and accumulated organic material supports surface and subsurface deposit-feeding burrowers. All marine sediments are anoxic at some depth below the sediment-water interface, and the depth of oxygen penetration generally varies with sediment type. In very fine sediments, occlusion of interstitial space limits the depth of oxygen diffusion to a few millimeters into the sediment (Revsbech et al., 1980). Environments with more shallow penetration of dissolved oxygen tend to support deposit-feeding taxa that are able to maintain some form of hydrologic contact with the sediment-water interface, via the manufacture of tubes or construction of irrigating burrows. 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 and facilitate feeding by carnivorous taxa that consume organisms occupying interstitial spaces (Fauchald and Jumars, 1979). Different sedimentary habitats support particular infaunal assemblages that tend to vary across time.

Epifauna

Many numerically dominant epifauna that inhabit inner shelf waters may more precisely be described as epibenthic, especially gastropods and decapods, although many of these taxa routinely are collected along with infauna when grab samplers are used. For example, certain epifaunal taxa, such as lady crabs (*Ovalipes* spp.), commonly burrow deeply into sediments, and adaptive behaviors of this type can complicate efforts to categorize such taxa into a specific, lifestyle-based, invertebrate group. In addition, 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.

Common epifaunal invertebrates occurring on open shelf bottoms offshore central east Florida include calico scallop (*Argopecten gibbus*), calico box crab (*Hepatus epheliticus*), iridescent swimming crab (*Portunus gibbesii*), brown shrimp (*Farfantepenaeus aztecus*), white shrimp (*Litopenaeus setiferus*), striped sea star (*Luidia clathrata*), and arrowhead sand dollar (*Encope michelini*) (Continental Shelf Associates, Inc., 1987). Wenner and Read (1982) reported on decapod crustaceans collected by trawl over a wide area of the SAB between Cape Fear, North Carolina and Cape Canaveral, Florida and found that site and species group distributions were related to depth. Moreover, depth related changes in groups were altered very little seasonally. Species groups consisted of an inner shelf assemblage, an open shelf assemblage, and an upper slope assemblage. As with infaunal invertebrates, epifaunal populations have distributions limited by depth-related variability of temperature and sedimentary habitat (Cerame-Vivas and Gray, 1966; Wenner and Read, 1982). Wenner and Read (1982) found an inner shelf assemblage that was numerically dominated by roughneck shrimp (*Rimapenaeus constrictus*), iridescent and blotched swimming crabs (*P. gibbesii and P. spinimanus*, respectively), and coarsehand lady crab (*Ovalipes stephensoni*).

Despite the fact that the area offshore eastern Florida is recognized as a zone of convergence of distinct faunal provinces (Briggs, 1974), most common epifauna in the study area are distributed over a wider geographic range. Striped sea star (*L. clathrata*) occurs in Atlantic waters from New Jersey coastal waters to Brazil (Downey, 1973). The sand dollar *Mellita quinquiesperforata*, a shallow water species, is another widely distributed taxon that occurs along most of the U.S. east coast south to the Brazilian coast (Serafy and Fell, 1985) and is often found in great numbers on sandy inner shelf areas (Day et al., 1971). The sand dollar *Encope michelini* occurs from Cape Hatteras to the southern tip of Florida and throughout the Gulf of Mexico (Hendler et al., 1995). Iridescent swimming crab (*P. gibbesii*) occurs from Massachusetts through the Gulf of Mexico and south to French Guiana, and the calico box crab (*Hepatus epheliticus*) is distributed from Chesapeake Bay to the Caribbean (Abele and Kim, 1986). Brown and white shrimps (*F. aztecus* and *L. setiferus*, respectively) occur as far north as Massachusetts and New York, respectively (Abele and Kim, 1986). Roughneck shrimp (*R. constrictus*) occurs from Chesapeake Bay (Virginia) to Brazil (Chace, 1972).

Certain epifauna are associated primarily 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 fine sediments, which are relatively unstable. Lyons (1989) found that certain mollusk species were most abundant in an offshore trough feature with poorly sorted sediments, whereas other mollusks were abundant on an offshore shoal that had well-sorted, coarse sediments. Decapods generally are found in areas of gravel and shell, although species such as *Crangon septemspinosa* tend to occur in areas of sand and the crab *Cancer irroratus* inhabits a variety of sediment types. Wenner and Read (1982) suggested that the combination of extremely variable sediments and temperatures may be sufficient to cause marked zonation between decapod assemblages on the outer shelf. Camp et al. (1977) collected inner shelf decapods offshore Hutchinson Island, Florida and found that an offshore sand shoal was numerically dominated by roughneck shrimp (*Rimapenaeus constrictus*), while an adjacent trough feature predominantly supported portunid crabs. Sand dollars such as *M. quinquiesperforata* most commonly are associated with sand habitats. 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

Ichthyofauna of eastern Florida is one of the most diverse and complex in the Western Atlantic. This high diversity is the consequence of environmental and biogeographic factors operating on various spatial and temporal scales (Gilmore, 1995, 2001). The primary environmental factor influencing fish distribution in the region is water temperature. Although the Gulf Stream current ameliorates water temperatures on the shelf throughout the region encompassed by the sand resource areas, atmospheric cooling and periodic upwellings also affect local water temperatures and in turn dictate the distribution of fishes. Seasonal drops in temperature affect inshore and coastal waters and limit the distribution of tropical species in inshore waters to about Sebastian, Florida (winter sea surface temperatures seldom fall below 20ºC south of 27º50') (Gilmore et al., 1978). Water temperatures on the outer shelf can decline rapidly as a result of periodic upwellings that originate along the shelf break (Atkinson and Targett, 1983; Smith, 1983; Pitts, 1999). The interplay between atmospheric cooling in shallow waters and upwelling cold water intrusions on the outer shelf results in a limited band of suitable water temperature in 18 to 55 m depths (Miller and Richards, 1979). A result of the varying temperature patterns in the region encompassed by the sand resource areas is that local assemblages are composed of species with differing thermal preferences and tolerances. Species inhabiting the region are usually grouped by their relative temperature tolerance into tropical, subtropical, and warm-temperate (Miller and Richards, 1979), or more detailed variations of these general categories (Gilmore, 1995).

Overlap between tropical, subtropical, and warm-temperate faunas underlies the transitional nature of the region's biogeography (Gilmore, 1995, 2001). In northern portions of the study area, near Sand Resource Areas A1, A2, and A3, warm-temperate species are more common and reach peak abundance in that region. At the southern end of the region, near Areas D1 and D2, more tropical species are present (Briggs, 1974; Gilmore, 1995). Consequently, the resulting ichthyofauna is composed of species with differing ecological and evolutionary histories that can be subdivided into several assemblages and eco-regions (Gilmore, 2001). This report describes fishes inhabiting waters of the study area by dividing the ichthyofauna into a demersal soft bottom assemblage (see below in this section), a demersal hard bottom assemblage (Section 2.3.1.2), and a pelagic assemblage (Section 2.3.2.1).

The demersal soft bottom fish assemblage that inhabits the open shelf off eastern Florida is composed of 213 species and 53 families (Gilmore et al., 1981; Gilmore, 2001).

The most speciose families include skates (Rajiidae), stingrays (Dasyatidae), torpedo rays (Torpedinidae), left-eye flounders (Bothidae), soles (Soleidae), cusk-eels (Ophidiidae), and searobins (Triglidae). Numerically abundant demersal fishes present on the open shelf include croakers, drums, and seatrouts (all three being sciaenids) and porgies (sparids).

As with most fishes, members of the eastern Florida demersal assemblage are distributed variably across space and time. Broad patterns are evident along cross shelf (bathymetic) and latitudinal axes as species segregate in recognizable assemblages. In the shallowest water depths, the surf zone, the demersal fish assemblage is characterized by kingfishes (*Menticirrhus* spp.), sand drum (*Umbrina coroides*), threadfins (*Polydactylus* spp.), and others (Peters and Nelson, 1987).

In shelf waters beyond the surf zone, the demersal assemblage is generally more diverse. The most comprehensive surveys of the eastern Florida demersal soft bottom assemblage have been conducted around Cape Canaveral and to the north using bottom trawl sampling gear (Anderson and Gehringer, 1965; Strushaker, 1969; Wenner and Sedberry, 1989). There has been very little information gathered on demersal soft bottom fishes of the study area. Certainly the smaller shelf width and higher proportion of hard bottom in the southern part have been deterrents to bottom trawling. In the northern portion of the project region, near Sand Resource Areas A1, A2, and A3, the demersal ichthyofauna is numerically dominated by sciaenids such as Atlantic croaker (*Micropogonias undulatus*), spot (*Leiostomus xanthurus*), silver seatrout (*Cynoscion nothus*), and star drum (*Stellifer lanceolatus*). Sciaenids are more typical of the demersal assemblage inhabiting the northern Gulf of Mexico than the assemblage found 50 km south along Florida's east coast (south of Areas C1 and C2). The contribution of these species to the northern assemblage decreases in a southerly direction, with sciaenids being uncommon to rare in the vicinity of Areas D1 and D2. Common groups found in shelf waters of the southern sand resource areas include searobins (*Prionotus* spp.), cusk-eels (*Lepophidium* spp.), snake eels (*Myrichthys* spp.), conger eels (*Hildebrandia* spp., *Heteroconger* spp.), and lizardfishes (*Synodus* spp., *Trachinocephalus myops*). These taxa are not as abundant as the sciaenids, thus the overall density of fishes in the southern region is likely to be much lower than that found in the mid- and northern sand resource areas.

Spawning is not well known for fishes in the entire region. However, Herrema et al. (1985) listed spawning periods for some common demersal soft bottom species (Table 2-1).

Endangered status of the smalltooth sawfish (*Pristis pectinata*) was finalized on 1 May 2003 (50 CFR Part 224). Critical habitat has not been defined and data are being collected on life history and biology of this species. Information that follows was obtained from NMFS (2000). The smalltooth sawfish is distributed in tropical and subtropical waters worldwide. Within U.S. waters, it was historically distributed throughout the Gulf of Mexico and along the Atlantic coast to North Carolina. This species has become rare in the northern Gulf of Mexico during the past 30 years and its known range is now reduced to the coastal waters of Everglades National Park in extreme southern Florida. Fishing and habitat degradation have extirpated the smalltooth sawfish from much of this former range. The smalltooth sawfish normally inhabits shallow waters (10 m or less) often near river mouths or in estuarine lagoons over sandy or muddy substrates, but also may occur in deeper waters (20 m) of the continental shelf. Shallow water less than 1 m seems to be important nursery

Table 2-1. Months of occurrence of demersal soft bottom[1], demersal hard bottom[2], and pelagic[3] fishes found in spawning condition off Hutchinson Island, Florida from January 1976 to June 1984 (Source: Herrema et al., 1985).

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lesser electric ray (*Narcine brasiliensis*) [1]						■						
Ladyfish (*Elops saurus*) [3]				■					■	■		
Purplemouth moray (*Gymnothorax vicinus*) [2]										■		
Sooty eel (*Bascanichthys bascanium*) [1]	■											■
Shrimp eel (*Ophichthus gomesi*) [1]		■		■								■
Palespotted eel (*O. ocellatus*) [1]	■											
Yellowfin menhaden (*Brevoortia smithi*) [3]	■	■	■	■							■	■
Atlantic menhaden (*B. tyrannus*) [3]	■	■	■								■	■
Menhaden (*B. smithi x tyrannus*) [3]	■	■	■									■
Scaled sardine (*Harengula jaguana*) [3]				■								
Atlantic thread herring (*Opisthonema oglinum*) [3]		■	■	■	■			■				
Spanish sardine (*Sardinella aurita*) [3]					■			■				
Cuban anchovy (*Anchoa cubana*) [3]		■		■								
Striped anchovy (*A. hepsetus*) [3]		■										
Longnose anchovy (*A. nasuta*) [3]				■								
Inshore lizardfish (*Synodus foetens*) [1]	■											
Hardhead catfish (*Arius felis*) [1]						■	■					■
Gafftopsail catfish (*Bagre marinus*) [1]			■									
Atlantic midshipman (*Porichthys plectrodon*) [1]		■										
Blotched cusk-eel (*Ophidion grayi*) [1]	■	■										
Bank cusk-eel (*O. holbrooki*) [1]	■	■		■	■	■			■		■	
Mooneye cusk-eel (*O. selenops*) [1]				■								
Lined seahorse (*Hippocampus erectus*) [1]		■			■					■		
Bull pipefish (*Syngnathus springeri*) [1]	■											
Tarpon snook (*Centropomus pectinatus*)												■
Snook (*C. undecimalis*)												■
Rock sea bass (*Centropristis philadelphica*) [1]	■	■	■									
Sand perch (*Diplectrum formosum*) [1]			■									
Bluefish (*Pomatomus saltatrix*) [3]	■	■	■	■	■	■	■		■	■		
Blue runner (*Caranx crysos*) [3]					■	■	■	■				
Atlantic bumper (*Chloroscombrus chrysurus*) [3]	■		■	■	■	■	■	■	■	■		
Round scad (*Decapturus punctatus*) [3]						■						
Leatherjacket (*Oligoplites saurus*) [3]					■	■						
Bigeye scad (*Selar crumenopthalmus*) [3]							■				■	■
Atlantic moonfish (*Selene setapinnis*) [3]						■			■	■	■	
Florida pompano (*Trachinotus carolinus*) [3]		■		■								
Gray snapper (*Lutjanus griseus*) [2]			■									■
Lane snapper (*L. synagris*) [2]				■	■	■	■					
Irish pompano (*Diapterus auratus*) [1]				■	■	■	■		■			
Striped mojarra (*D. plumieri*) [1]					■	■	■					
Silver jenny (*Eucinostomus gula*) [1]					■							
Yellowfin mojarra (*Gerres cinereus*) [1]										■		
Black margate (*Anisotremus surinamensis*) [2]	■		■	■								
Porkfish (*A. virginicus*) [2]		■			■					■		
Tomtate (*Haemulon aurolineatum*) [2]						■						
Sailors choice (*H. parrai*) [2]					■							
White grunt (*H. plumieri*) [2]					■	■						
Pigfish (*Orthopristis chrysoptera*) [1]	■	■	■	■	■							■
Sheepshead (*Archosargus probatocephalus*) [2]	■	■	■	■							■	
Sea bream (*A. rhomboidalis*) [2]				■	■				■			
Silver porgy (*Diplodus argenteus*) [2]	■	■	■	■	■							■
Pinfish (*Lagodon rhomboides*) [1]	■	■	■	■							■	■
Silver perch (*Bairdiella chrysoura*) [1]		■	■									
Striped croaker (*B. sanctaeluciae*) [2]	■	■	■	■		■						
Silver seatrout (*Cynoscion nothus*) [1]	■	■	■	■					■	■	■	■
Weakfish (*C. regalis*) [1]	■	■	■	■					■			■
Banded drum (*Larimus fasciatus*) [1]		■	■	■	■	■			■	■	■	■
Spot (*Leiostomus xanthurus*) [1]	■	■	■	■					■	■	■	
Southern kingfish (*Menticirrhus americanus*) [1]	■	■	■	■	■	■	■	■		■	■	
Gulf kingfish (*M. littoralis*) [1]		■	■	■	■		■	■				
Northern kingfish (*M. saxatilis*) [1]	■						■			■		
High-hat (*Equetus acuminatus*) [2]		■	■	■								
Atlantic croaker (*Micropognius undulatus*) [1]	■	■	■						■	■	■	■
Black drum (*Pogonias cromis*) [1]		■	■									
Sand drum (*Umbrina coroides*) [1]	■	■	■	■					■		■	■
Atlantic spadefish (*Chaetodipterus faber*) [2]			■	■	■							
Striped mullet (*Mugil cephalus*) [3]	■	■									■	■
White mullet (*M. curema*) [3]	■		■	■	■	■	■	■	■	■		■
Great barracuda (*Sphyraena barracuda*) [2]								■				
Guaguanche (*S. guachancho*) [2]							■		■			
Dusky jawfish (*Opistognathus whitehursti*) [2]												■
Bigeye stargazer (*Dactyloscopus crossotus*) [1]				■								
Southern stargazer (*Astroscopus y-graecum*) [1]			■									
Hairy blenny (*Labrisomus nuchipinnis*) [2]		■	■									
Checkered blenny (*Starksia ocellata*) [2]		■										
Oyster blenny (*Hypleurochilus aequipinnis*) [2]	■	■				■	■					
Orangespotted blenny (*H. springeri*) [2]	■	■										
Seaweed blenny (*Parablennius marmoreus*) [2]		■							■			
Seminole goby (*Microgobius carri*) [2]			■									
Atlantic cutlassfish (*Trichiurus lepturus*) [1/3]					■	■		■	■	■	■	■
Frigate mackerel (*Auxis thazard*) [3]					■		■					
Little tunny (*Euthynnus alletteratus*) [3]							■					
Spanish mackerel (*Scomberomorus maculatus*) [3]			■	■	■	■	■	■	■			■
Harvestfish (*Peprilus alepidotus*) [3]						■						
Butterfish (*P. triacanthus*) [3]	■	■		■								
Smoothhead scorpionfish (*Scorpaena calcarata*) [2]					■							
Striped searobin (*Prionotus evolans*) [1]	■											■
Blackwing searobin (*P. salmonicolor*) [1]		■	■	■	■			■				
Leopard searobin (*P. scitulus*) [1]	■	■	■	■	■	■			■		■	■
Bighead searobin (*P. tribulus*) [1]	■		■			■						
Spotted whiff (*Citharichthys macrops*) [1]		■	■	■								
Southern flounder (*Paralichthys lethostigma*) [1]	■	■										■
Broad flounder (*P. squamilentus*) [1]			■									
Shoal flounder (*Syacium gunteri*) [1]		■										
Lined sole (*Achirus lineatus*) [1]								■				
Naked sole (*Gymnachirus melas*) [1]	■											
Southern puffer (*Sphoeroides nephelus*) [1]		■										

area for young smalltooth sawfish. Smalltooth sawfish grow slowly and mature at about 10 years of age. Females bear live young and the litters reportedly range from 15 to 20 embryos requiring a year of gestation. Diet consists of macroinvertebrates and fishes such as herrings and mullets. The saw is reportedly used to rake surficial sediments in search of crustaceans and benthic fishes or to slash through schools of herrings and mullets.

2.3.1.2 Hard Bottom

Epibiota

Hard bottom habitats on the continental shelf off eastern Florida consist of rock outcrops colonized by various algae, sponges, hard corals, soft corals, fire corals, tunicates, and other sessile invertebrates that constitute the epibiota. Much of the rock substrate underlying these epibiotal assemblages is composed of relict Pleistocene beach ridges that generally parallel the present-day shoreline (Meisburger and Duane, 1971). These ridges follow general trends along a north-south axis and tend to protrude variably above the sedimentary layer in a discontinuous fashion. Exposed rock will vary in relief from a level pavement to ledges as high as 4 m. In areas where rock substrate is exposed for adequate periods of time, epibiota will assemble through larval settlement from the water column. Such assemblages are thought to take decades to develop into mature communities composed of long-lived organisms (Dayton, 1984). Within the region encompassed by the sand resource areas, hard bottom tracts exist in offshore (shelf) and nearshore (0 to 4 m depths) waters. Offshore hard bottom forms three general trends: shallow shelf, intermediate shelf, and outer shelf (Miller and Richards, 1979; Perkins et al., 1997). A single hard bottom trend occurs in nearshore waters of the project area (South Atlantic Fishery Management Council [SAFMC], 1998b; Lindeman and Snyder, 1999).

Epibiota colonizing offshore and nearshore hard bottom varies in taxonomic composition and diversity in both north-south and cross-shelf directions. Variations in light penetration, water temperature, salinity, sedimentation, and circulation all may influence the structure and dynamics of epibiotal assemblages. Unfortunately, there has been no directed study of epibiotal assemblages or environmental factors controlling the assemblages along eastern Florida north of the Palm Beach area. General trends such as the north-south gradient in species diversity and basic taxonomic composition have been described peripherally for some epibiotic taxa, including corals and algae (Humm, 1969; Briggs, 1974; van den Hoek, 1975; Searles and Schneider, 1980; Jaap, 1984), but specific details of assemblage organization within the region remains unknown.

Nearshore hard bottom outcrops along the shoreline are usually composed of beach rock (Anastasia limestone) and subject to frequent sediment burial and erosion caused by high wave energy. Despite this physically demanding environment, several sessile organisms are well adapted and often cover high portions of the exposed rock. One such organism is the sabellarid polychaete *Phragmatopoma lapidosa*, which forms large gregarious colonies commonly referred to as wormrock (Kirtley and Tanner, 1968). Other epibiota common on nearshore hard bottom of the region are boring sponge (*Cliona celata*), as well as brown (*Padina* and *Dictyota*) and red (*Bryothamnion*) algae (Juett et al., 1976). Hard and soft corals are rare in nearshore habtiats, with only *Siderastrea radians*, *Pseudopterogorgia americana*, *P. acerosa*, and *Muricea muricata* occasionally occurring. Wormrock supports associated assemblages of organisms such as decapod crustaceans (Gore et al., 1978).

Offshore hard bottom trends generally support more dense and diverse epibiotal assemblages than those found on nearshore hard bottom (e.g., Goldberg, 1973). Although data are sparse for areas north of Palm Beach, some general trends are evident, in particular the latitudinal trend in decreasing diversity and colony size of species such as hard corals. Algae, sponges, hard corals, and soft corals are the most conspicuous components of the epibiota colonizing the offshore hard bottom and are described below.

Algae occur on offshore hard bottom as members of four ecological groups: 1) coralline algae that form crusts over exposed rock substrate; 2) fleshy and filamentous algae that attach to the rock substrate; 3) algae that attach to unconsolidated sediments; and 4) excavating or boring algae (Jaap, 1984). The taxonomic composition of algae of the region includes major algal phyla such as blue-green (Cyanobacteria), brown (Phaeophyta), green (Chlorophyta), and red (Rhodophyta) (Littler and Littler, 2000). Species composition of these groups has not been well documented for the region, but it appears that red algae are most speciose when compared with blue-green, brown, and green (Juett et al., 1976; Eiseman, 1979). Some fleshy species, particularly the green algae *Codium* and *Caulerpa*, undergo explosive blooms near Sand Resource Areas D1 and D2 (Continental Shelf Associates, Inc. and Florida Atlantic University [FAU], 1994). *Codium* blooms were followed by large amounts of decomposing algae accumulating on hard bottom areas, causing death and degradation of sponges, soft corals, and other attached organisms (Continental Shelf Associates, Inc. and FAU, 1994). Offshore hard bottom areas of the region generally support more species of algae than nearshore hard bottom areas (Searles and Schneider, 1980).

Sponges commonly found on offshore hard bottom include ball (*Ircinia* spp.), boring (*Cliona* spp.), loggerhead (*Spheciospongia vesparium*), rope (*Amphimedon* sp.), and various encrusting taxa (*Spiralstrella*; *Mycale*). Sponges cover considerable portions of exposed rock and essentially replace hard corals as the largest colonizers of hard bottom north of Sand Resource Areas D1 and D2 (Miller and Richards, 1979). Large sponges contribute habitat complexity and relief in otherwise low relief hard bottom areas.

Hard corals exist on offshore hard bottom as colonial or solitary forms. These species are most abundant and diverse on hard bottom near the southern sand resource areas (C1, C2, D1, and D2). In this portion of the study area, frequently occurring colonial corals include members of the following genera: *Diploria*, *Isophyllia, Mycetophyllia*, *Montastrea*, and *Solenastrea*. Solitary corals found in this area include *Astrangia* and *Phyllangia*. The most widespread hard coral species in the region north of Areas D1 and D2 is ivory tree coral (*Oculina varicosa*). This species reaches peak coverage and growth in deeper waters of about 100 m near the shelf edge where it forms reefs or banks, but small colonies occur on hard bottom areas throughout the region from Jupiter Inlet to just south of Cape Canaveral (Avent et al., 1977; Reed, 1980). Some *Oculina* reefs have been designated by the SAFMC as marine reserves (see Appendix E**,** Figure E-10) due to their documented importance as habitat for fishes and invertebrates (Reed et al., 1982; Koenig et al., 2000).

Soft corals are common on hard bottom throughout the region and the overall species composition is not known. Species known to occur on shelf hard bottom include *Eunicea*, *Gorgonia*, *Plexaurella*, *Lophogorgia*, and *Pseudopterogorgia* (Jaap, 1984; SAFMC, 1998b).

Demersal Fishes

Offshore and nearshore hard bottom areas of the region provide extensive habitat for fishes (Miller and Richards, 1979; Lindeman and Snyder, 1999). Off central east Florida, offshore hard bottom habitats support at least 255 fish species from 49 families (Gilmore et al., 1981). More recent estimates have increased the number to at least 385 species (Gilmore, 1995). The most speciose families ranked by numbers of species are gobies, parrotfishes, grunts, seabasses, snappers, damselfishes, and wrasses. Most species from these families are considered to be tropical or subtropical in origin, and their distributions are greatly influenced by water temperature.

In addition to water temperature, hard bottom fish distribution and abundance are influenced by the same factors (Gulf Stream, temperature range, shelf width, and habitat diversity) discussed previously for soft-bottom demersal fishes. As with demersal fishes and epibiota, a north-south gradient exists for diversity and composition of hard bottom fishes. The distribution and abundance of tropical fishes varies with latitude and distance across the shelf from the western edge of the Gulf Stream. A more diverse tropical assemblage exists in the southern region of the study area (near Areas C1, C2, D1, and D2) and many of these species are gradually lost or displaced offshore in a northward direction along the shelf. North of Sebastian, Florida (near Areas B1 and B2), warm temperate and subtropical fishes are restricted to a depth band ranging from 18 to 55 m with a center of distribution in the 33 to 40 m water depth range. Thermal effects of the Gulf Stream are thought to be the primary cause of this gradient (Miller and Richards, 1979).

Nearshore hard bottom habitats support an estimated 192 fish species (Gilmore et al., 1981; Vare, 1991; Lindeman and Snyder, 1999). These species are derived from families of tropical reef fishes such as angelfishes (Pomacanthidae), butterflyfishes (Chaetodontidae), damselfishes (Pomacentridae), wrasses (Labridae), parrotfishes (Scaridae), surgeonfishes (Acanthuridae), snappers (Lutjanidae), and porgies (Sparidae). One species of tropical origin, striped croaker (*Bairdiella sanctaluciae*), is found in the U.S. only in the region from Jupiter to Sebastian. Abundant species associated with nearshore hard bottom habitats include sailors choice (*Haemulon parra*), porkfish (*Anisotremus virginicus*), cocoa damselfish (*Stegastes variabilis*), silver porgy (*Diplodus argenteus*), and hairy blenny (*Labrisomus nuchipinnis*). Many of these species are present as early life stages, indicating the importance of nearshore hard bottom as essential fish habitat (Lindeman and Snyder, 1999).

Offshore hard bottom areas support a suite of species similar to that found on nearshore hard bottom, but diversity is generally higher. Again, most of these species are reef fishes of tropical origin, and several examples of the transitional nature of the region are found. Mutton snapper (*Lutjanus analis*), yellowtail snapper (*Ocyurus chrysurus*), sailors choice (*Haemulon parra*), schoolmaster (*Lutjanus apodus*), and dog snapper (*Lutjanus jocu*) reach northern limits within the area encompassed by the sand resource areas (Gilmore and Hastings, 1983). There is some cross-shelf segregation of species in the area, but this is more evident in the northern portion of the study area where inshore temperature ranges are more variable and tropical elements of the assemblage are displaced offshore. Nevertheless, the most obvious cross-shelf faunal break occurs at the outer shelf. Species common on deeper reefs but not generally found shallower than 30 m are wrasse bass (*Liopropoma eukrines*), bank butterflyfish (*Chaetodon aya*), tattler (*Serranus phoebe*), and yellowtail reeffish (*Chromis enchrysurus*). Species that typify intermediate reefs are blue angelfish (*Holacanthus bermudensis*), spotfin butterflyfish (*Chaetodon ocellatus*), reef butterflyfish (*C. sedentarius*), jacknife-fish (*Equetus lanceolatus*), and hogfish (*Lachnolaimus maximus*).

Most hard bottom species found in the study area spawn within the region. Some species, such as gag (*Mycteroperca microlepis*), may migrate into the region for spawning. Table 2-1 presents spawning times for some hard bottom species off Hutchinson Island, Florida.

In addition to natural hard bottom, artificial reefs and structures play hard bottom roles. Concrete, fiberglass, limestone, steel, and various other materials have been accidentally or purposely sunk on the shelf within the study area (see Appendix E, Figures E-6, E-8, E-9, and E-10). Most of the same epibiota and fishes discussed above will colonize artificial structures within this area.

2.3.2 Pelagic Environment

2.3.2.1 Fishes

Pelagic fishes are represented by 200 species in the region (Gilmore et al., 1981). Primary families occurring in the region are mackerels and tunas (Scombridae), jacks (Carangidae), driftfishes (Stromateidae), anchovies (Engraulidae), and herrings (Clupeidae).

Pelagic fishes can be subdivided into oceanic and coastal pelagic components. Oceanic pelagic species are the highly migratory epipelagic fishes including billfishes *Istiophorus platypterus*, *Makaira nigricans*, and *Tetrapterus* spp., tunas *Thunnus* spp., *Euthynnus alleteratus*, and *Katsuwonus pelamis*, wahoo (*Acanthocybium solanderi*), and dolphin (*Coryphaena* spp.) that rarely venture far into shelf waters, preferring the warmer and clearer Gulf Stream. These species will enter shelf waters, especially when environmental conditions are optimum, but they are more common within the Gulf Stream. Because the Gulf Stream is very close to shore in this region, particularly in the southern portion of the study area, oceanic pelagic fishes will often occur in the vicinity of the sand resource areas.

Another group of fishes found in oceanic waters are those species that associate with drifting flotsam. Floating seaweed (the brown alga *Sargassum*), jellyfishes, siphonophores, and driftwood attract juvenile and adult epipelagic fishes (Dooley, 1972; SAFMC, 2002). As many as 100 fish species are closely associated with floating *Sargassum* at some point in their life cycle, but only 2 spend their entire lives there: the sargassumfish (*Histrio histrio*) and sargassum pipefish (*Syngnathus pelagicus*) (Dooley, 1972; SAFMC, 2002). Most fishes associated with *Sargassum* are temporary residents, such as juveniles of species that reside in shelf or coastal waters as adults. However, several larger species of recreational or commercial importance, including Atlantic bonito, blackfin tuna, dolphin, little tunny, skipjack tuna, wahoo, and yellowfin tuna, feed on small fishes and invertebrates attracted to *Sargassum*.

Coastal pelagic species prefer shelf waters and usually range from near shore to the shelf break. Coastal pelagic fishes can be divided into two ecological groups. The first group includes large predatory species such as bluefish (*Pomatomus saltatrix*), cobia (*Rachycentron canadum*), jacks (*Caranx* spp.), king (*Scomberomorus cavalla*) and Spanish (*S. maculatus*) mackerels, little tunny (*Euthynnus alletteratus*), and sharks (*Carcharhinus* spp.). With the exception of sharks that tend to be slow growing and have low fecundity, these species typically form schools, undergo migrations, grow rapidly, mature early, and exhibit high fecundity. Each of these species is important to some extent to regional recreational and commercial fisheries. The second group exhibits similar life history characteristics, but the species are smaller in body size and are planktivorous. This group is composed of anchovies (*Anchoa* spp.), bigeye scad (*Selar crumenophthalmus*), menhaden (*Brevoortia* spp.), round scad (*Decapterus punctatus*), Spanish sardine (*Sardinella aurita*), and Atlantic thread herring (*Opistonema oglinum*). These species form large schools in inner shelf and coastal waters, where they are often preyed on by members of the larger predatory coastal pelagic group.

All members of the coastal pelagic group migrate north and south, and east and west over the shelf area encompassed by the sand resource areas. Migratory patterns for most species are not well known. In general, as water and air temperatures decrease in early winter, bluefish, pompano, and Spanish mackerel will migrate southward along the coast. In mid-shelf waters, cobia and king mackerel migrate from either direction. King mackerel exists in at least two populations in the western Atlantic, the Atlantic group and Gulf of Mexico group (Sutter et al., 1991; Gold et al., 1997). The Gulf of Mexico group migrates from near the Mississippi Delta eastward, then southward around the Florida peninsula, wintering off southeastern Florida (Sutter et al., 1991). The Atlantic population migrates between Cape Hatteras and southern Florida. In winter and spring, both populations migrate to southeastern Florida, where they overlap to an unknown extent (Gold et al., 1997). Little tunny migrate into shelf waters during spring and summer months, moving to shelf edge waters to spawn.

Coastal pelagic fishes spawn in shelf or shelf edge waters. Although precise spawning locations are not well documented, eggs and larvae of most species occur throughout the study area. The Gulf Stream transports spawning products into the study area from other regions, and associated eddies retain locally spawned eggs and larvae within the area. Some pelagic species, such as bigeye scad (*Selar crumenopthalmus*), move from offshore waters into nearshore waters to spawn (Continental Shelf Associates, Inc., 1992). Spawning periods for pelagic species are given in Table 2-1.

Some coastal pelagic species are found in the nearshore environment along sandy beaches from the shoreline to the swash zone (Peters and Nelson, 1987). This habitat occurs along the coast for the entire study area. Nearshore fish assemblages show considerable seasonal structuring. The lowest abundance of all species occurs in winter, with peak numbers found during summer and fall. Large predatory species (particularly bluefish, jacks, sharks, and Spanish mackerel) may be attracted to large concentrations of anchovies, herrings, and silversides that congregate in nearshore areas. Mullets, particularly striped mullet (*Mugil cephalus*) and white mullet (*M. curema*), are seasonal members of the coastal pelagic assemblage when adults migrate downstream to the ocean to spawn. During fall months throughout the study area, large schools of striped mullet migrate along the coast, usually from north to south in response to cold fronts and other atmospheric disturbances.

2.3.2.2 Sea Turtles

Five sea turtle species may occur on the eastern Florida inner shelf (shoreline to the 20-m isobath). In order of abundance, they are the loggerhead, green, hawksbill, Kemp's ridley, and leatherback sea turtles (Table 2-2). In general, this region appears to be an important year-round habitat for juvenile through adult loggerhead and green sea turtles on both the inner shelf and mid-shelf (20- to 40-m isobath). Hawksbill, Kemp's ridley, and leatherback sea turtles also are found year-round, although they primarily utilize the mid-shelf and (in the case of leatherbacks) the outer shelf and continental slope (Teas, 1993).

Table 2-2. Sea turtle species potentially occurring offshore east Florida. Species are listed in order of relative abundance.

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

[a] Status: E = endangered, T = threatened under the Endangered Species Act of 1973.

[b] 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.

All sea turtles in U.S. territorial waters are protected under the ESA of 1973. Currently, leatherbacks and Kemp's ridleys are listed as endangered species and loggerheads are listed as a threatened species. Green sea turtles also are listed as a threatened species, except for the Florida breeding population, which is listed as an endangered species. Due to inability to distinguish between the latter two populations away from the nesting beach, green sea turtles are considered as an endangered species wherever they occur in U.S. waters (National Marine Fisheries Service [NMFS] and U.S. Fish and Wildlife Service [USFWS], 1991).

South Brevard County, including beach habitats west of Sand Resource Areas A1, A2, B1, and B2, has the greatest density of sea turtle nests in Florida and probably produces more turtle hatchlings per kilometer than any other beach in Florida (Ehrhart and Witherington, 1987). Loggerhead, green, and leatherback turtles account for most nests in the area (Meylan et al., 1995).

Loggerhead Sea Turtle

The loggerhead sea turtle (*Caretta caretta*), named for its characteristic broad and massive skull, is a relatively large sea turtle. This species occurs throughout tropical, subtropical, and temperate waters of the Atlantic, Pacific, and Indian Oceans (Dodd, 1988). In the western Atlantic, it is found in estuarine, coastal, and shelf waters from South America to Newfoundland. Loggerhead adults and subadults are generalist carnivores, feeding primarily on benthic crustaceans (particularly crabs) and mollusks (Dodd, 1988).

Four genetically distinct loggerhead nesting subpopulations have been identified in the western North Atlantic (Marine Turtle Expert Working Group, 2000). These are 1) the Northern Nesting Subpopulation, extending from North Carolina to northeastern Florida, at approximately 29° N; 2) the South Florida Nesting Subpopulation, extending from 29° N on the Florida east coast to Sarasota on its west coast; 3) the Florida Panhandle Nesting Subpopulation; and 4) the Yucatan Nesting Subpopulation. Loggerhead turtles within the study area belong to the South Florida Nesting Subpopulation.

Loggerhead turtles are present year-round in Florida waters, with peak abundance during spring and fall migrations. Off Cape Canaveral, loggerheads utilize both the inner shelf and mid-shelf during all seasons except winter, when they tend to congregate on the mid-shelf (Schroeder and Thompson, 1987). Henwood (1987) found that three distinct groups of loggerheads (adult males, adult females, and subadults) moved into inner shelf waters off Cape Canaveral at different times of the year. Adult males were most abundant in April and May, adult females from May to July, and subadults during the remainder of the year. These data suggest that nesting adult females are short-term residents that migrate into the area on 2- and 3-year intervals and reside elsewhere during non-nesting years. Adult males do not seem to migrate with adult females but may reside in the vicinity of nesting beaches throughout the year. Subadults forage opportunistically along the Atlantic seaboard, although evidence suggests that a resident population of subadults overwinter in the Canaveral area each year (Henwood, 1987).

Ninety percent of loggerhead nesting in the U.S. occurs in south Florida (Shoop et al., 1985). Their nesting season in southeast Florida (meant here as Brevard County through the Florida Keys) is reported to extend from late April through September. March and April are transitional months for loggerheads off Cape Canaveral, Florida. Juveniles, which are thought to overwinter in the area, depart and are replaced by adult males that migrate into the area to mate (Ryder et al., 1994). The southeast Florida region supports the largest loggerhead nesting aggregation in the western hemisphere (Schroeder and Thompson, 1987). Annual numbers of South Florida Nesting Subpopulation nests in southeast Florida during 1989 to 1998 ranged from 46,295 (1989) to 74,988 (1998), with a mean of 61,731 nests annually (Marine Turtle Expert Working Group, 2000). A study of loggerhead nest distributions along Cape Canaveral found that nesting sites were not distributed randomly and peak nesting areas were revisited annually. In most cases, nest densities were correlated to increased beach slope and decreased offshore bathymetric contours (Provancha and Ehrhart, 1987).

Following nesting activities, many adult loggerheads disperse to islands in the Caribbean Sea, waters off southern Florida, and Gulf of Mexico (Meylan and Bjorndal, 1983; Nelson, 1988). Hatchling loggerheads swim offshore and begin a pelagic existence within *Sargassum* rafts, drifting in current gyres and convergence zones 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).

Green Sea Turtle

The green sea turtle (*Chelonia mydas*), named for the greenish color of its body fat, has a circumglobal distribution in tropical and subtropical waters. The species is made up of several distinct populations. In the U.S., green turtles occur 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).

Juveniles and subadult green turtles are found year-round within the Mosquito Lagoon portion of the Indian River Lagoon system on Florida's east coast. Immature turtles also may be found on the inner shelf along the entire east coast of Florida; however, relatively low numbers of green turtles have been captured in the Cape Canaveral area, presumably the result of this species' habitat preference (Schmid, 1995; Hirth, 1997).

Primary nesting sites in U.S. Atlantic waters are high-energy beaches along the east coast of Florida, primarily during July and August, with additional sites in the U.S. Virgin Islands and Puerto Rico (NMFS and USFWS, 1991; Hirth, 1997). Hatchlings swim out to sea and enter a pelagic stage in *Sargassum* mats associated with convergence zones and eddies.

Adult green turtles commonly feed on algae, seagrasses, and associated organisms, using reefs and rocky outcrops near seagrass beds for resting areas. The major feeding grounds for green turtles in U.S. waters are located in Florida, where the turtles forage mainly on algae and the seagrass *Thalassia testudinum* (Burke et al., 1992). Juveniles transition 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 southeast Florida coast, Florida Keys, Bahamas, Caribbean Sea, and southwestern Gulf of Mexico (NMFS and USFWS, 1993). Along the east Florida coast, hawksbills are probably year-round residents, including adults, subadults, and juveniles (B. Brost, 2002, personal communication, Florida Marine Research Institute [FMRI], St. Petersburg, FL).

Nesting areas for hawksbills in the Atlantic are found in south Florida, Puerto Rico, and the U.S. Virgin Islands. Within the continental U.S., nesting beaches are restricted to the southeastern coast of Florida (i.e., Palm Beach, Broward, and Dade Counties), Florida Keys, and southwestern coast of Florida as noted by Meylan (1992) and the NMFS and USFWS (1993). Hawksbill nesting along the east Florida coast occurs between June and September (B. Brost, 2002, pers. comm.).

Adult hawksbills typically are associated with coral reefs and similar hard bottom areas, where they forage on invertebrates, primarily 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 (Meylan, 1988; Ernst et al., 1994).

Kemp's Ridley Sea Turtle

The Kemp's ridley (*Lepidochelys kempi*) is the smallest and most endangered of the sea turtles. Its distribution includes the Gulf of Mexico and the southeast U.S. coast, although some individuals have been found as far north along the eastern seaboard as Nova Scotia and Newfoundland (Marine Turtle Expert Working Group, 1996b). Adult Kemp's ridleys are found almost exclusively in the Gulf of Mexico, primarily on the inner shelf (Byles, 1988).

Kemp's ridleys found along east Florida are primarily juveniles and subadults that use waters of the inner shelf as developmental habitat, although adult-sized individuals also are occasionally found (Schmid and Ogren, 1992). They move northward along the coast with the Gulf Stream in spring to feed in productive, inner shelf waters between Georgia and New England (NMFS and USFWS, 1992a). These migrants then move southward with the onset of cool temperatures in late fall and winter (Lutcavage and Musick, 1985). The Cape Canaveral, Florida area seems to serve as an important winter foraging ground, based on high capture and recapture rates from October to March (Schmid and Ogren, 1992; Schmid, 1995). Telemetry studies of Kemp's ridley migrations off the U.S. east coast suggest that they do not establish residency in dredged shipping channels during this period, although they have been observed on occasion in and around these channels (Gitschlag, 1996). Recent evidence suggests that immature or subadult individuals that move to the Atlantic inner shelf may return to the Gulf of Mexico as adults to nest on Mexican beaches (Witzell, 1998).

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, 1992a; Weber, 1995; Marine Turtle Expert Working Group, 2000). In the U.S., nesting occurs infrequently on Padre and Mustang Islands in south Texas and in a few other Gulf of Mexico locations (Marine Turtle Expert Working Group, 2000).

After emerging, Kemp's ridley hatchlings swim offshore to inhabit *Sargassum* mats and drift lines associated with convergences, eddies, and rings. 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, 2000).

Post-pelagic (juvenile, subadult, and adult) Kemp's ridleys feed primarily on portunid crabs, but also occasionally eat mollusks, shrimps, dead fishes, and vegetation (Mortimer, 1982; Lutcavage and Musick, 1985; Shaver, 1991; NMFS and USFWS, 1992a; Burke et al., 1993; Werner and Landry, 1994).

Leatherback Sea Turtle

The leatherback sea turtle (*Dermochelys coriacea*), named for its unique, flexible carapace, is a circumglobal species that is currently subdivided into two subspecies. The Atlantic subspecies, *D.c. coriacea,* inhabits waters of the western Atlantic 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).

Adult leatherback turtles reportedly occur in east Florida waters primarily during summer, although leatherback turtles were sighted during recent aerial survey programs conducted off northeast Florida from October through April as well (Schroeder and Thompson, 1987; Knowlton and Weigle, 1989; Continental Shelf Associates, Inc., 2002). During these surveys, leatherbacks were sighted on the mid-shelf and inner shelf but not usually near shore (Continental Shelf Associates, Inc., 2002). However, historic data suggest that leatherbacks also may utilize inner shelf waters during periods of local thermal fronts that concentrate food resources (Thompson and Huang, 1993).

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. Nests in Brevard County are relatively few in number when compared with Florida beaches to the south, especially Martin and Palm Beach Counties (NMFS and USFWS, 1992b; B. Brost, 2002, pers. comm.). Nesting along the east Florida coast occurs between late February through early September (Meylan et al., 1995). Because of the cryptic behavior of hatchling and/or juvenile leatherback turtles, very little is known of their pelagic distribution.

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 (Grant et al., 1996). Foraging has been observed at the surface, but considering their well developed deep-diving capabilities, it also is likely to occur at depth (Eckert, 1995).

2.3.2.3 Marine Mammals

Approximately 27 marine mammal species may occur off east Florida (Table 2-3). However, only a few species are typically found on the inner shelf, including North Atlantic right whale, humpback whale, Florida manatee, bottlenose dolphin, and Atlantic spotted dolphin. Marine mammals listed as endangered or threatened under the ESA 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

Two species of endangered cetaceans are likely to occur in shelf waters off east Florida during at least some part of the year. They are the North Atlantic right whale, *Eubalaena glacialis*, and humpback whale, *Megaptera novaeangliae*. North Atlantic right whales are seasonal “residents” in inner shelf and mid-shelf waters. Inner shelf waters in the northern part of the study area are designated as a critical habitat for North Atlantic right whales (Appendix E, Figure E-10). Humpback whales are only rarely present as transients during their spring and fall migrations.

One endangered sirenian, the Florida manatee (*Trichechus manatus latirostris*), is a year-round “resident” species within Florida inshore and inner shelf waters. Inner shelf waters of the study area are designated as critical habitat for the Florida manatee.

The study area is within the distributional range of four other endangered cetaceans (blue whale, *Balaenoptera musculus*; fin whale, *B. physalus*; sei whale, *B. borealis*; and sperm whale, *Physeter macrocephalus*), but they are considered unlikely to be present within inner shelf waters of the study area. The sperm whale is a deepwater (i.e., water depths offshore of the continental shelf break) species throughout its range (Roden, 1998), and blue, fin, and sei whales would not be expected to occur on the inner shelf as far south as Florida (Waring et al., 1999).

Table 2-3. Marine mammal species potentially occurring offshore east Florida.

Scientific Name	Common Name	Status[a]	Presence[b]
ORDER CETACEA	**WHALES AND DOLPHINS**		
Suborder Mysticeti	**Baleen Whales**		
Family Balaenidae	**Right and Bowhead whales**		
Eubalaena glacialis	North Atlantic 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	O
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
Stenella clymene	Clymene dolphin	none	O
Pseudorca crassidens	False killer whale	none	O
Orcinus orca	Killer whale	none	O
Stenella attenuata	Pantropical spotted dolphin	none	O
Feresa attenuata	Pygmy killer whale	none	O
Globicephala macrorhynchus	Short-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
ORDER SIRENIA	**MANATEES AND DUGONGS**		
Trichechus manatus latirostris	Florida manatee	E	X

[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).

[b] **Presence**: (X) presence likely during at least some season; (O) presence possible but unlikely due to geographic range, preference for deeper waters, or uncommon occurrence.

North Atlantic Right Whale

North Atlantic 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 (New England Aquarium, 2004). 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 the 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 to calving grounds within inner shelf waters off southeastern Georgia and northeastern Florida occurs from mid-October to early January (Kraus et al., 1993). 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 calving grounds off southeastern Georgia and northeastern Florida. Sand Resource Areas A1, A2, A3, and B1 are located within or in close proximity to the southern extension of the northern right whale critical habitat (Appendix E**,** Figure E-10). Right whales are commonly found within their designated winter critical habitat during their calving season, which generally extends from approximately December through March.

Humpback Whale

In the northern Atlantic Ocean, 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). There have been numerous sightings and strandings off the Mid-Atlantic and southeastern U.S. coast, particularly during winter and spring (Wiley et al., 1995). Humpbacks occasionally stray onto the mid- and inner shelf off northeast and north central Florida, primarily between January and April. These individuals are considered to be strays from the main migratory population, moving southward during this period (S. Swartz, 2002, pers. comm., NMFS, Miami, FL). 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 along the U.S. eastern seaboard have been identified in the western Gulf of Maine and the Great South Channel (Massachusetts).

Florida Manatee

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. This group constitutes a separate subspecies known as the Florida manatee (*Trichechus manatus latirostris*) that can be divided into at least two virtually separate populations, one centered along the Atlantic coast and the other on the Gulf coast of Florida (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).

Florida manatees inhabit both saltwater and freshwater 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 6 km off the Florida coast (USFWS, 1996). During winter months, the manatee population confines itself to inshore and inner shelf waters of the southern half of peninsular Florida and to springs and warm water outfalls (e.g., power plant cooling water outfalls) just beyond northeastern Florida (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). Critical habitats for manatees have been identified by the USFWS. Distributions of these critical habitat areas in peninsular Florida are fragmented along the southwest and east coasts and include inner shelf waters within the study area (USFWS, 1996; B. Brooks, 2001, pers. comm., USFWS).

Non-Listed Species

Odontocete Whales and Dolphins

The most common non-listed marine mammal occurring on the east Florida inner shelf is the bottlenose dolphin (*Tursiops truncatus*), which may be present year-round. 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, based on two ecotypes: a coastal, warm water ecotype and a deepwater ecotype (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). Bottlenose dolphins present within the inner shelf waters of the study area would most likely represent the shallow water ecotype, although this area may include numerous localized, resident stocks (Blaylock and Hoggard, 1994; Waring et al., 1999). Within inner shelf and mid-shelf waters off east Florida, including the study area, bottlenose dolphins feed primarily on fishes, and to a much lesser degree on cephalopods (squids), crustaceans (primarily shrimps), and xiphosurans (horseshoe crabs) (Barros and Odell, 1990; Barros, 1993). Mating and calving occur from February to May. The calving interval is 2 to 3 years. They normally occur in relatively small group sizes, but also may be found in groups of up to several hundred individuals.

Also potentially occurring in inner shelf 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 normally inhabits the outer shelf and slope, although southern populations occasionally come into mid-shelf and inner shelf waters (Waring et al., 1999). Favored prey includes herring, 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.

Other non-listed odontocetes potentially occurring off east Florida but typically in deep waters along the shelf edge and beyond include dwarf and pygmy sperm whales (*Kogia simus* and *K. breviceps*), Clymene dolphin (*Stenella clymene*), false killer whale (*Pseudorca crassidens*), killer whale (*Orcinus orca*), pantropical spotted dolphin (*Stenella attenuata*), pygmy killer whale (*Feresa attenuata*), Risso's dolphin (*Grampus griseus*), rough-toothed dolphin (*Steno bredanensis*), short-finned pilot whale (*Globicephala macrorhynchus*), spinner dolphin (*Stenella longirostris*), and striped dolphin (*Stenella coeruleoalba*) (Roden, 1998; Waring et al., 1999; Wynne and Schwartz, 1999). Although beaked whales (*Mesoplodon* spp. and *Ziphius cavirostris*) also may occur, their distribution at sea is poorly known, and they are believed to be principally deepwater species.

Mysticete Whales

Two non-listed species of mysticete whales may occur in east Florida waters: Bryde's whale (*Balaenoptera edeni*) and minke whale (*B. acutorostrata*). Both are predominantly found in more northerly waters and are infrequently sighted on the east Florida inner shelf (Winn, 1982).

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, the 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 Office of Coast 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 to 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 were 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 provided a direct method of documenting potential environmental impacts related to sand mining on the OCS.

3.1.1 Previous Studies

The present study area is located on the central east coast of Florida, bounded to the north by False Cape and to the south by Jupiter Inlet (Figure 3-1). The continental shelf narrows from a maximum width of about 48 km near Cape Canaveral to a minimum of about 16 km in the southern extent of the study area as it merges with the Florida-Hatteras slope. This reduction in shelf width is accompanied by a distinct increase in shelf steepness (Field and Duane, 1974). Beaches along this region of the east coast of Florida are composed primarily of siliceous sand and sandy gravel mixed with large quantities of shell fragments (Figure 3-2; McLaren and Hill, 2002). South of Port Canaveral, beach sediment becomes increasingly coarse and shell-enriched in response to the existence of local coquina outcrops (Field and Duane, 1974). Sediment is eroded from offshore shoals and northern beaches and is transported to southern beaches as southward-directed littoral transport. Source material is added locally into the littoral drift system from large exposures of coquinoid limestone that are present from 1 m below mean low water (MLW) to the berm crest between Cocoa and Canova Beaches (Field and Duane, 1974). The shoreline in this region exists as five barrier islands separated from each other by inlets and from the mainland by the Intracoastal Waterway, which includes the Banana and Indian Rivers. Each inlet is armored with rock jetties to control channel migration. Maintenance dredging has been practiced periodically at all entrances during the study time period to maintain channel navigability. Some of the greatest shoreline changes that occur along the outer coast of Florida were the result of interrupted longshore transport at these inlets. Additionally, navigation structures used to control channel migration and shoaling may result in erosion and deposition “hot spots” along beaches adjacent to inlets. Often, material dredged from the channels has been recycled back into the littoral transport system through placement on beaches immediately south of entrances.

Numerous studies have been completed by Federal, State, and local agencies to evaluate shoreline evolution for beach management and protection purposes. The Florida Beach Erosion Control Program, implemented in 1964, created three interrelated programs administered by the Florida Department of Environmental Protection (FDEP), including the Coastal Construction Control Line (CCCL) program, the Beach Erosion Control Program, and the Coastal Construction Program. In support of the CCCL program, historical shoreline positions for the entire coast of Florida were digitized and developed for the Florida Department of Natural Resources (DNR) Division of Beaches and Shores historical shoreline database (Foster, 1992). This database includes all historical USC&GS topographic sheets from the 1850s to the 1980s (Demirpolat and Tanner, 1991). In addition, aerial photography and beach profiles surveyed from fixed DNR survey points (“R” monuments) have been added to the database. R-monuments are spaced at approximately 300 m along the entire Florida coast, and profiles have been surveyed periodically by the Coastal Data Acquisition System since the early 1970s. Initial data collection efforts in support of the CCCL program were implemented on a county-by-county basis, with emphasis on beach protection and inlet management on a county-wide scale. In the five counties that make up the present study area (Brevard, Indian River, St. Lucie, Martin, and Palm Beach), shore protection projects have been implemented since the late 1950s and have included beach nourishment along various segments of coast (Figure 3-3).

In 1986, the FDEP, as part of the Beach Erosion and Control Program, developed a comprehensive beach management planning program designed to identify areas of shoreline erosion within the State and seek mitigation strategies. In the five counties that make up the present study area, a total of 86 km of shoreline currently is identified as critically eroded (Florida DEP Office of Beaches and Coastal Systems, 1999). Critical erosion areas for each county are summarized in Figure 3-4. For all counties, erosion is attributed to winter northeast storms, tropical storms, hurricanes, and the effects of inlets. A large component of areas designated as critically eroded exist immediately downdrift of entrances. Inlet management plans have been developed for all entrances within the study area. A summary of inlet development and maintenance information is presented in Table 3-1.

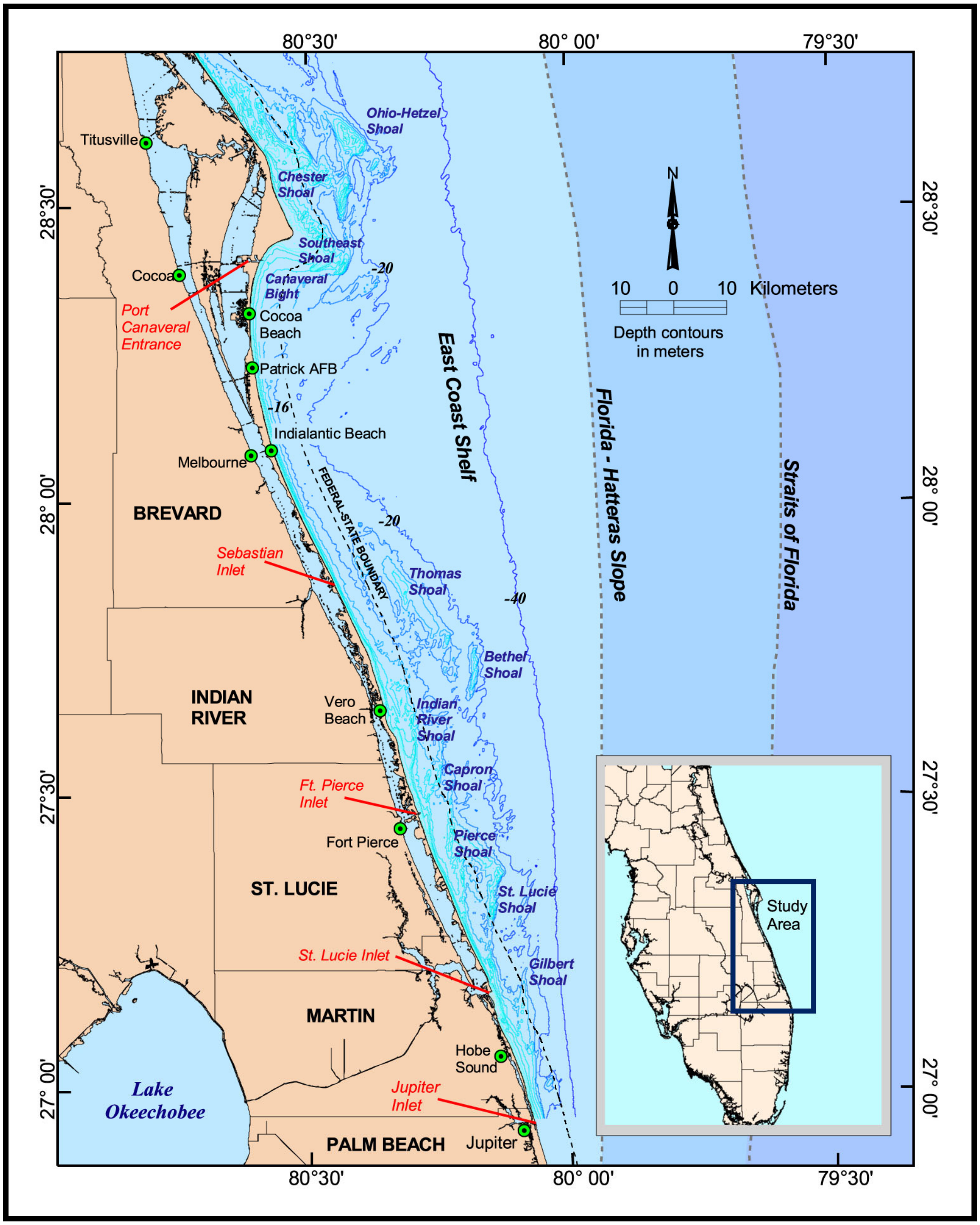

Figure 3-1. Study location diagram.

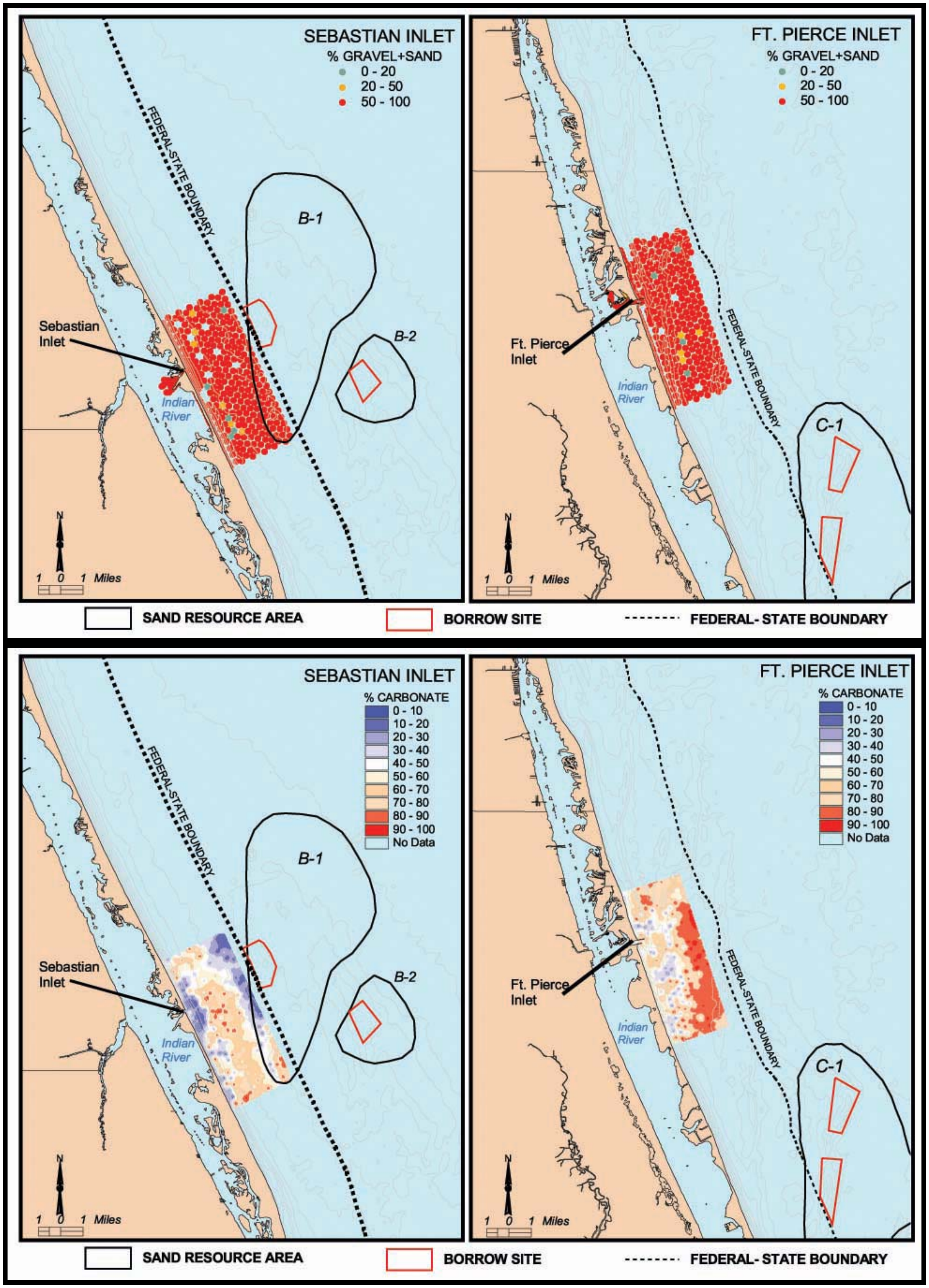

Figure 3-2. Sediment grain-size and carbonate distribution at Ft. Pierce and Sebastian Inlets (data collected by GeoSea Consulting Ltd. in December 2001).

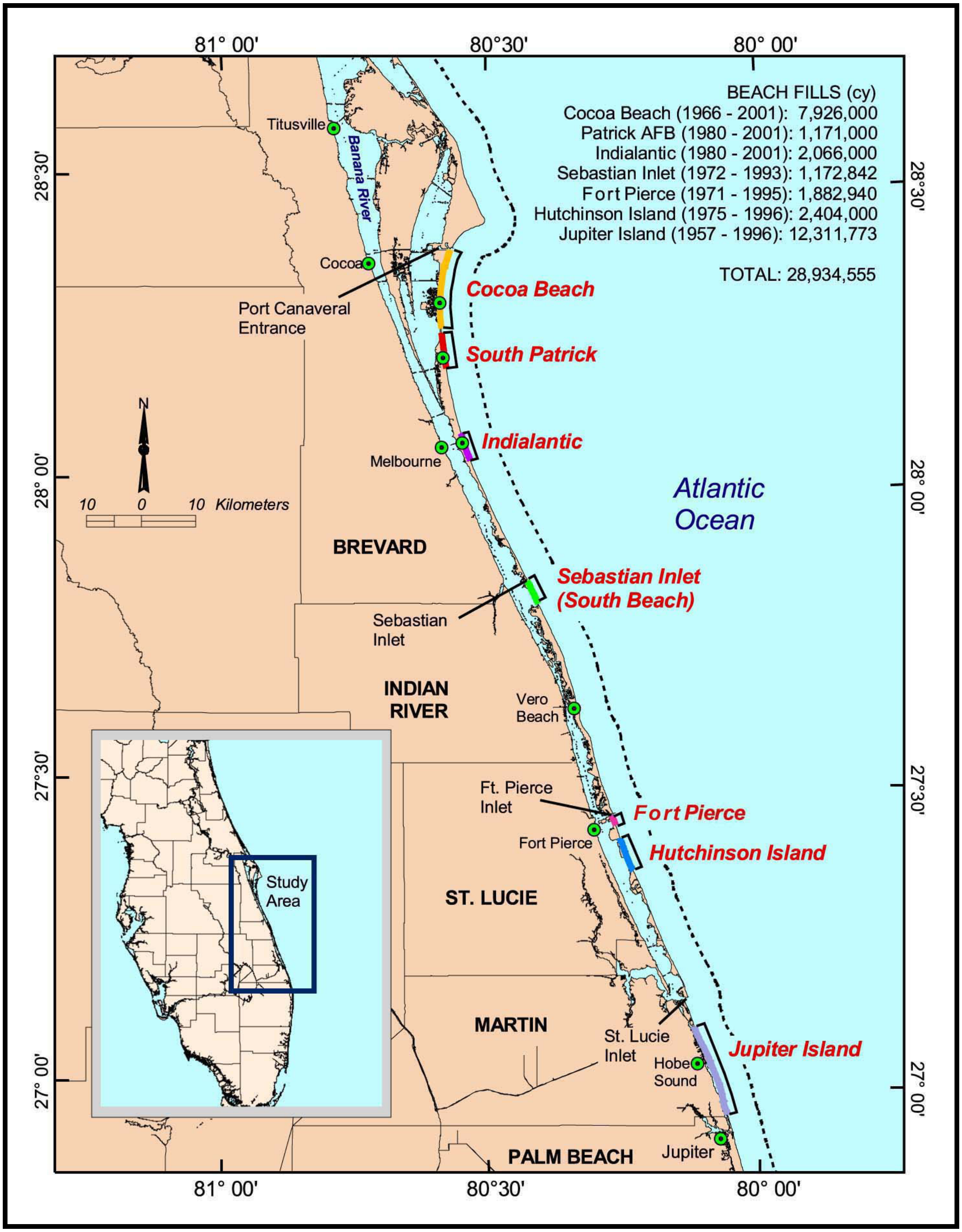

Figure 3-3. Beach fill activities between 1957 and 2001.

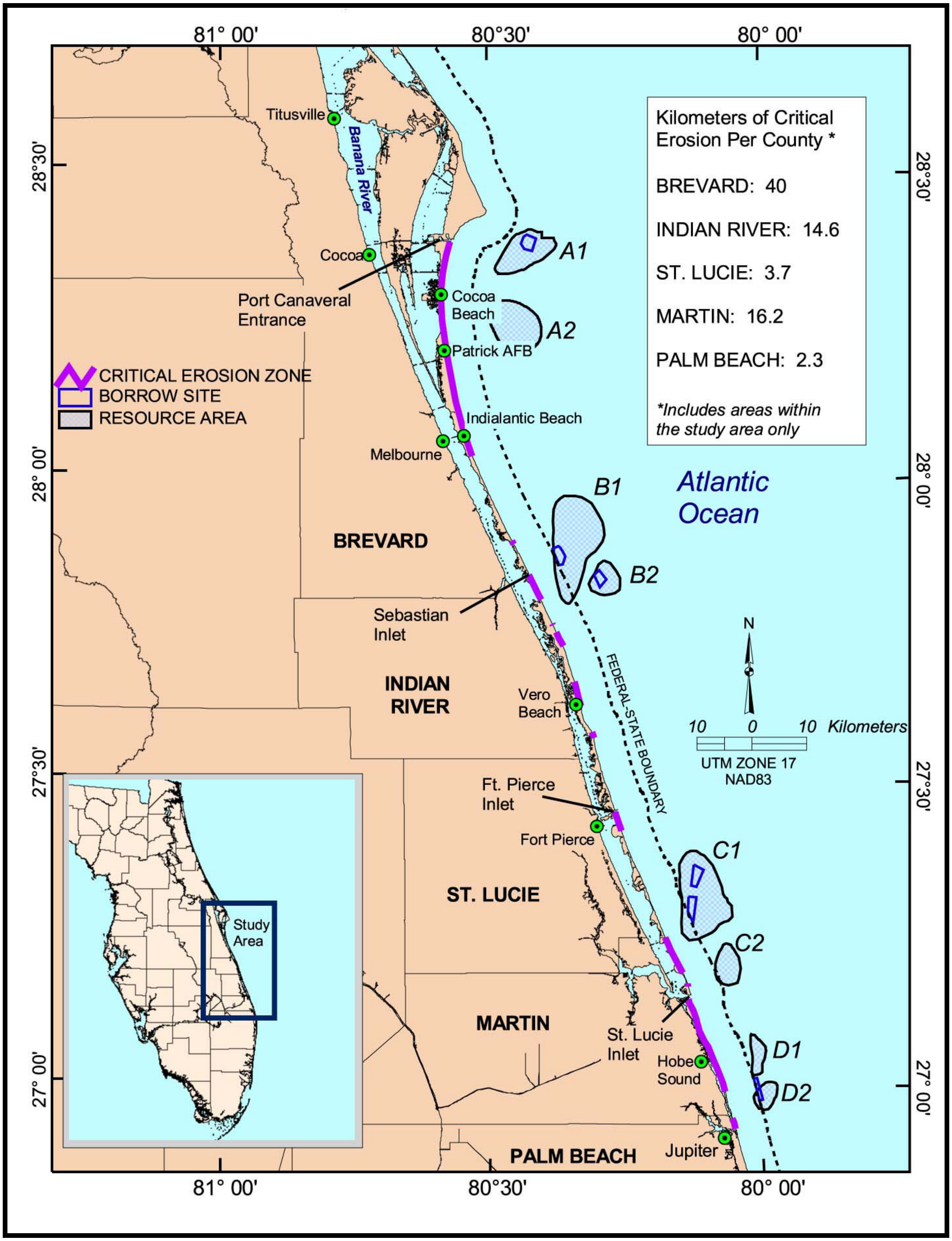

Figure 3-4. Areas designated by the Florida Department of Environmental Protection as Critical Erosion Zones.

Table 3-1. Summary of inlet management activities.

Inlet	Initial Development	Maintenance Dredging	South Side Beach Nourishment	Reference
Port Canaveral Inlet	1951 to 1954	Currently maintained to -46 ft MLW. Maintenance dredging done every 12 to 18 months.	Since 1966 some sediment from inlet and some from offshore.	Florida DEP and Canaveral Port Authority (1996)
Sebastian Inlet	1919 to 1924	Maintenance dredging of channel and sand trap occurs periodically. Inlet management plan in March 2000 established annual bypassing objective of 56,000 m^3 (70,000 cy).	Additional material from an upland source also is occasionally placed on downdrift beaches.	Florida DEP Office of Beaches and Coastal Systems (2000)
Ft. Pierce Inlet	1920 to 1921	Initially dredged in 1938 and deepened in 1996. Maintenance dredging conducted on a biannual basis since 1978.	Since 1978, disposal of inlet material.	Florida DEP and St. Lucie County (1997)
St. Lucie Inlet	1916 to 1929	Current Federally authorized features were completed in 1982. Maintenance dredging conducted at approximately 4-year intervals.	Dredged material is placed within a 1.6 km segment of beach.	Florida DEP and Martin County (1995)
Jupiter Inlet	1922	Maintenance dredging of the channel and sand trap occurs generally on an annual basis. Approximately 57,000 m^3 (75,000 cy) estimated for bypassing on an annual basis.	Sediment is bypassed annually and is periodically supplemented by sediment dredged from the Intracoastal Waterway.	Florida DEP and Jupiter Inlet District (1997)

Recent beach protection and sediment management efforts in Florida have shifted from a county-wide basis to a more regional approach. The Statewide Coastal Monitoring Program was implemented in 2000 with the objective of acquiring monitoring data on a regional scale. The FDEP Office of Beaches and Coastal Systems (OBCS) has developed a regional data collection plan that identified four coastal regions within which comprehensive data collection will occur on a recurring annual cycle (Leadon, 2002). Data collection began as part of this program in 2000 and is scheduled to continue annually through 2005. The extent of the present study area is in the southeast region and was scheduled for data collection in 2002. Data collected include digital aerial photography, FDEP beach profile surveys, and wave data (Leadon et al., 2001; data available at http://www.dep.state.fl.us/beaches/data/coastmon.htm). Of the recently collected data, aerial photography, beach profile, and wave data were used as part of this study. Aerial photos were used to delineate the high-water shoreline in Martin and Palm Beach Counties to complete the most recent composite shoreline (1996/2002). Beach profile data were evaluated to assist in determining berm crest elevation for developing bathymetric surfaces, and wave gage data from the nearshore wave gage installed at Melbourne Beach were incorporated in the waves section of this report. Recent data collection efforts by the FDEP also include sediment sampling. About 700 grab samples were taken in December 2001 by GeoSea Consulting Ltd. to characterize sediment grain size, composition, and transport processes at Fort Pierce and Sebastian Inlets (McLaren and Hill, 2002). Data from this collection effort were used for evaluating sediment characteristics adjacent to sand resource areas.

3.1.2 Shoreline Position Data Base

Eight outer coast high-water shoreline surveys were used to quantify historical shoreline change between 1878/83 and 2002 (Table 3-2). The first four surveys were conducted by the USC&GS in 1877/83, 1928, 1942/48, and 1970. Digital data for these topographic field surveys (T-sheets) and tide-coordinated photographic surveys (TP-sheets; 1970) were compiled from historical maps by Demirpolat and Tanner (1991), and were obtained from the FDEP website in AutoCAD drawing (dwg) format. The remaining four surveys were completed in 1996, 2000, and 2002 (differential global positioning system [DGPS] field surveys and aerial photography). Because individual survey extents did not encompass the entire study area, the four data sets were combined to create a composite shoreline representing the time period 1996/2002. Three of these surveys are DGPS field surveys conducted in May 1996, June 2000, and June 2002, and the fourth is a shoreline interpreted from 2002 orthorectified aerial photography. The DGPS surveys were conducted by Applied Coastal using a Trimble Pro/XR differential GPS, and the aerial photography was obtained from the FDEP website. The high-water shoreline was interpreted from 2002 orthorectified aerial photography by Applied Coastal personnel. Horizontal position of the high-water shoreline for DGPS surveys was determined visually using a hierarchy of criteria dependent on morphologic features present on the subaerial beach. The primary criterion was a well-marked limit of uprush by waves associated with high tide. This generally was recognized on the beach as the berm crest (Figure 3-5). If a berm crest did not exist, a debris line could usually be identified, below which the beach face was smooth from the action of wave swash and backwash. The criteria adopted are consistent with those used by field topographers and photo interpreters in developing NOS T- and TP-sheet shorelines (Swainson, 1928; Shalowitz, 1964). All high-water shoreline data were projected into a common horizontal coordinate system and datum, in this case Universal Transverse Mercator (UTM) Zone 17N, North American Datum of 1983 (NAD83).

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

Positional errors for each shoreline can be calculated using the information in Table 3-3; however, change analysis requires comparing two shorelines from the same geographical area but different time periods. Table 3-4 summarizes potential errors associated with change analyses computed for specific time intervals. As expected, maximum positional errors are aligned with the oldest shorelines (1877/83, 1928, and 1948) at smallest scale (1:20,000), but most change estimates for the study area document shoreline advance or retreat greater than these uncertainty estimates.

3.1.3 Historical Change Trends

Regional change analyses provided an assessment of shoreline response for comparison with predicted changes in wave-energy focusing at the shoreline resulting from potential offshore sand dredging activities. They differ from previous qualitative analyses in that continuous measurements of shoreline change are provided at 50-m alongshore intervals for the period 1877/83 to 2002. As such, model results (wave and sediment

Table 3-2. Florida shoreline source data characteristics.

Date	Data Source	Comments and Map Numbers
1877/83	USC&GS Topographic Maps (1:20,000)	First regional survey completed with standard engineering techniques. 1877 - Cape Canaveral to Cocoa Beach (T-sheets 1450a, 1450b). 1878 - Indialantic to Sebastian Inlet (T-sheets 1460, 1478). 1880/82 - Sebastian Inlet to Fort Pierce Inlet (T-Sheets 1544, 1630). 1883 - Fort Pierce to Jupiter Inlets (T-Sheets 1650, 1652, 1640).
1928	USC&GS Topographic Photomaps (1:20,000)	Second regional survey completed throughout study area. All maps produced from interpreted aerial photography. Cape Canaveral to Jupiter Inlet.
1942/48	USC&GS Topographic Photomaps (1:20,000)	All maps produced from interpreted aerial photography. 1942 - St. Lucie Inlet to Jupiter Inlet (T-sheets 8411, 8412, 8413, and 8414). 1946 - Wabasso to St. Lucie Inlet (T-sheets 8841, 8842, 8844, 8845). 1947 - 4 miles north of Cocoa Beach to Wabasso (T-sheets 8880, 8882, 8884, 8886, 8888). 1948 - False Cape to 4 miles north of Cocoa Beach (T-sheet 9174).
1970	USC&GS Topographic Photomaps in cooperation with the State of Florida (1:10,000)	All photomaps produced from interpreted aerial photography. (TP-sheets 135, 136, 138, 140, 142, 143, 145, 146, 147, 149).
1996	DGPS Survey (1:1)	North Boundary of Cape Canaveral National Seashore to Sebastian Inlet. Data collected by Applied Coastal using a Trimble Pro/XR.
2000	DGPS Survey (1:1)	North of Sebastian Inlet to north of Fort Pierce Inlet. Data collected by Applied Coastal using a Trimble Pro/XR.
2002	DGPS Survey (1:1)	South jetty of Port Canaveral to the north jetty of Sebastian Inlet.
2002	Orthorectified Aerial Photography	North of Fort Pierce Inlet to the southern border of Martin County. Aerial photos obtained from the FDEP website; high-water shoreline interpreted by Applied Coastal personnel.

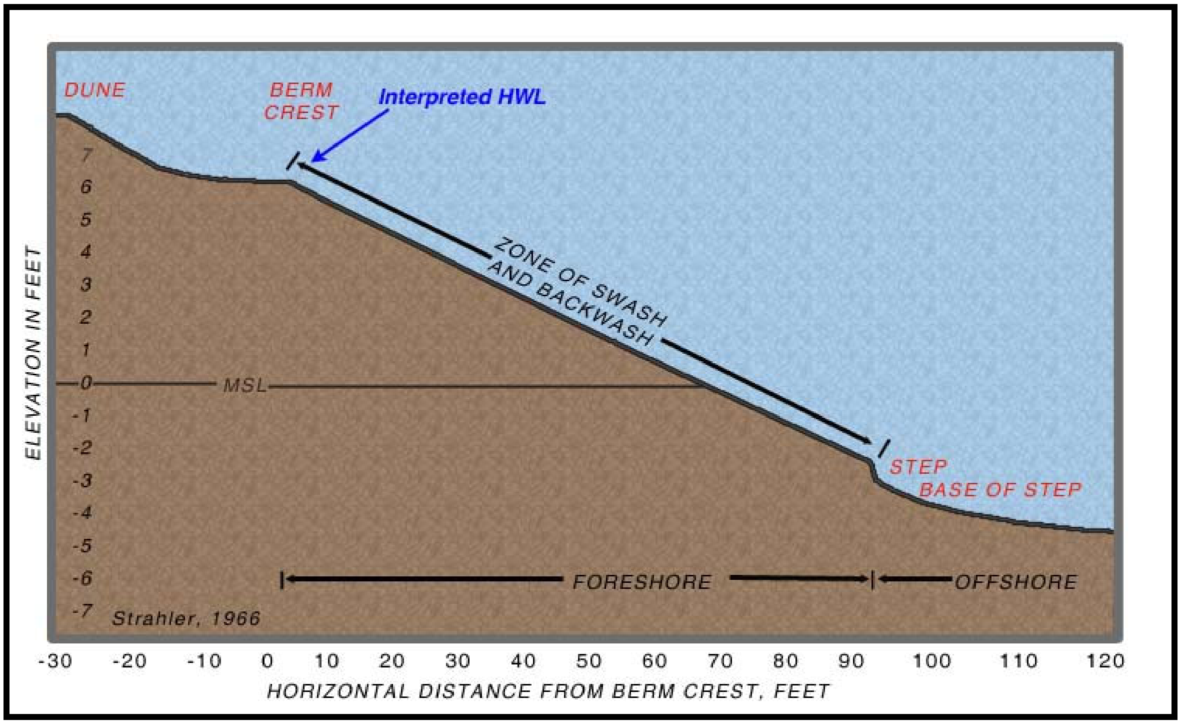

Figure 3-5. High-water shoreline position classification referenced to the beach berm crest.

Table 3-3. Potential error estimates associated with Florida shoreline position surveys.

Traditional Engineering Field Surveys (1877/83 shoreline)		
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 (1877/83, 1928, 1942/48, and 1970)	**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
Historical Aerial Surveys (1928, 1942/48, and 1970)	**Map Scale**	
	1:10,000	1:20,000
Delineating high-water shoreline position	±5 m	±10 m
DGPS Surveys (1996, 2000, and 2002 shorelines)		
Delineating high-water shoreline	±1 to 3 m	
Position of measured points	±2 to 5 m (specified) ±1 to 3 m (field tests)	
Digital Aerial Photo Surveys (2002 shoreline)		
Delineating high-water shoreline	±5 m	
Aerial photo registration error	±1 m (RMS error report)	
Sources: Shalowitz, 1964; Ellis, 1978; Anders and Byrnes, 1991; Crowell et al., 1991.		

Table 3-4. Maximum root-mean-square potential error for Florida shoreline change data.

Year	1928	1942/48	1970	1996-2002 DGPS	2002 Aerial
1877/83	±22.6[1]	±22.6	±22.6	±16.3	±16.0
	(±0.5)[2]	(±0.3)	(±0.3)	(±0.1)	(±0.1)
1928		±23.7	±18.7	±17.7	±17.5
		(±1.2)	(±0.5)	(±0.3)	(±0.3)
1942/48			±18.7	±17.7	±17.5
			(±0.5)	(±0.3)	(±0.3)
1970				±10.2	±9.8
				(±0.4)	(±0.3)

[1] 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).

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 (1877/83 to 1928, 1928 to 1948, 1948 to 1970, and 1970 to 1996/2002) relative to net, long-term trends in the study area (1877/83 to 1970 and 1877/83 to 1996/2002).

3.1.3.1 1877/83 to 1928

The time period 1877/83 to 1928 summarized net shoreline change relative to natural coastal processes and human-induced changes at Sebastian, Fort Pierce, and St. Lucie Inlets. Variation in shoreline response associated with south-directed net longshore transport and construction of entrance jetties is visible throughout the study area during this time period. Shoreline change along ocean beaches from the northern limit of the study area to immediately north of Cape Canaveral (a distance of about 5 km) illustrated continuous erosion due to northeast storm impacts and south-directed longshore transport. Calculated recession rates ranged from 0.3 to 2.0 m/yr, with an average recession rate of 1.6 m/yr. This trend showed a distinct reversal along the shoreline south of this area for beaches adjacent to the Canaveral Bight. During this time period, the shoreline from the northern tip of Cape Canaveral to approximately 20 km south showed the greatest amount of deposition over the entire study area as substantial quantities of sand being transported from the north. South of this point for about 72 km (near Vero Beach), shoreline response was characterized by alternating zones of minor erosion and accretion, with most change exhibiting erosion. Greatest changes along this stretch of shoreline were associated with the creation of Sebastian Inlet between 1919 and 1924. A maximum erosion rate of 1.2 m/yr was recorded about 460 m south of the entrance, with the maximum accretion rate of 0.7 m/yr existing immediately north of the inlet (Figure 3-6). The shoreline south of this point for the next 19 km was primarily depositional, with some areas of erosion. Construction of jetties at Fort Pierce Inlet between 1920 and 1921 caused shoreline change similar to that observed at Sebastian Inlet, with deposition observed along the north side of the entrance and erosion to the south. Variation in response within this 19-km length of shoreline was more than twice the variation in rates observed immediately to the north. Recession rates varied to a maximum of about 1.5 m/yr, and deposition rates were less than about to 2.9 m/yr. From a point just south of Fort Pierce Inlet to the southern limit of the study area at Jupiter Inlet, the shoreline exhibited almost continuous erosion. This area showed the greatest amount of shoreline recession over the entire study area, with a maximum rate of about 16.8 m/yr associated with the development of St. Lucie Inlet between 1916 and 1929. Erosion rates remained high from St. Lucie Inlet south for about 11 km, where the shoreline became more stable and alternated between minor erosion and accretion to Jupiter Inlet.

3.1.3.2 1928 to 1948

Between 1928 and 1948, maximum rates of shoreline advance and recession again were observed at beaches along the south shore of Cape Canaveral and to the south of St. Lucie Inlet, respectively. Overall, shoreline response illustrated an increase in net deposition from that observed during the previous time period (Figure 3-7). The shoreline north of Cape Canaveral experienced erosion followed by an extensive zone of deposition along beaches adjacent to Canaveral shoals, similar to trends observed in this region between 1877 and 1928. This indicates that south-directed longshore transport continued to dominate shoreline response in this region. Recession rates on the northern side of Cape Canaveral ranged up to 7.4 m/yr, similar to those observed during the previous time period. Unlike shoreline change trends observed between 1877 and 1928, shoreline advance was dominant south of Cape Canaveral for about 153 km to St. Lucie Inlet between 1928 and 1948, with only minor erosional aberrations along small stretches of coast. Similar change trends were documented at Fort Pierce Inlet, with deposition north of the entrance and erosion to the south (Figure 3-7). Shoreline advance also was prominent along the north side of St. Lucie Inlet, with a maximum rate of 8.9 m/yr due to construction of a jetty along the north side of the inlet around 1928. South of St. Lucie Inlet, net shoreline recession was dominant for about 10 km. Erosion during this period (maximum of 7.1 m/yr), while smaller in magnitude than that observed between 1877/83 and 1928, was similar to that observed north of Cape Canaveral. South of this erosion zone, the change trend again returned to deposition.

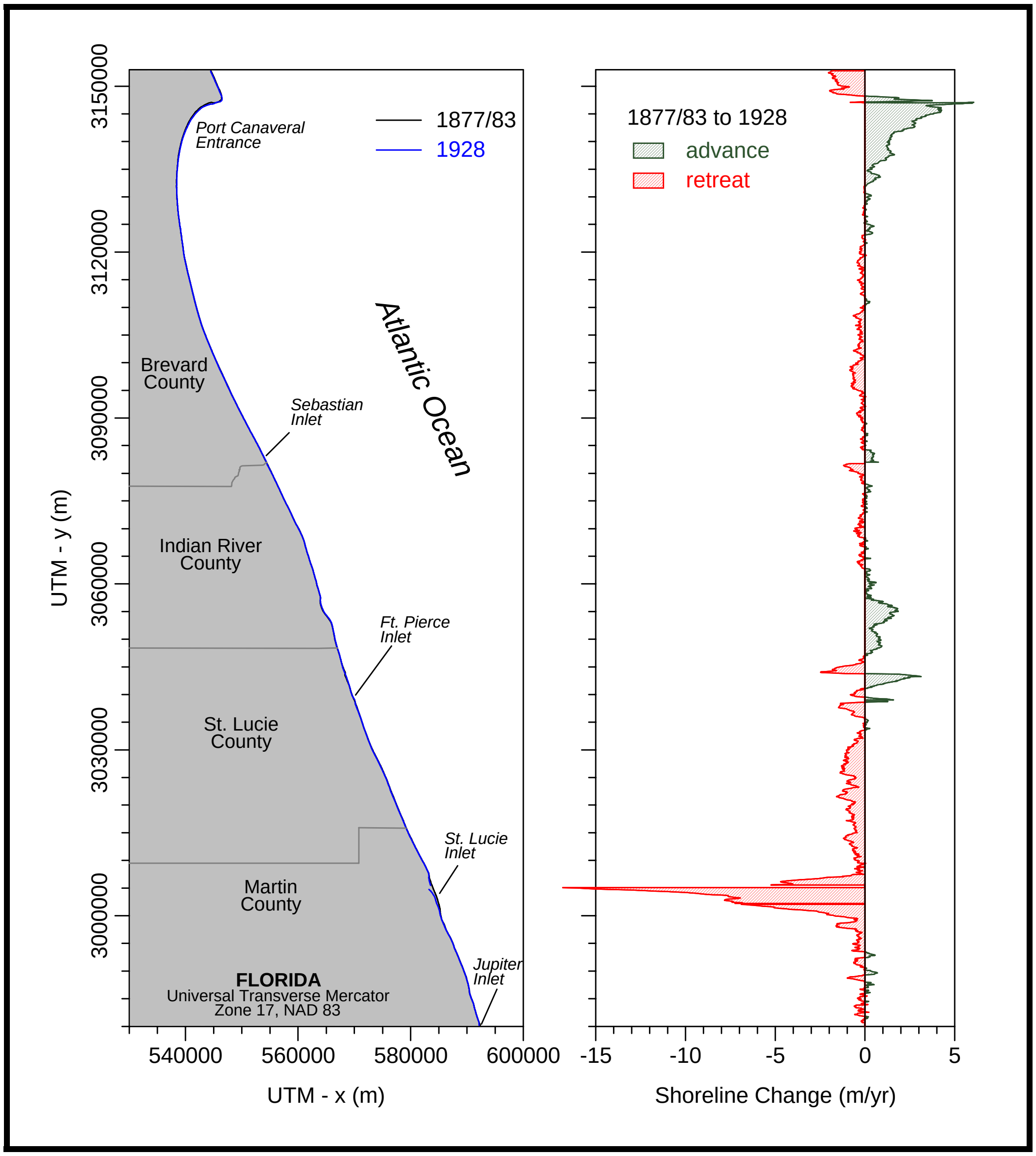

Figure 3-6. Shoreline position and change between False Cape and Jupiter Inlet, FL, 1877/83 to 1928.

3.1.3.3 1948 to 1970

Shoreline change between 1948 and 1970 illustrated similar overall trends to those observed during the previous 70 years. Maximum deposition again was observed along beaches on the south side of Cape Canaveral, and maximum erosion was located south of St. Lucie Inlet (Figure 3-8). The largest difference from the previous 70 years of shoreline change was observed north and south of Port Canaveral, which was developed as a Federal navigation project between 1951 and 1954 (Kraus et al., 1999). The beach north of the entrance experienced increased deposition immediately north of the north jetty to a maximum rate of 9.5 m/yr, and the south side of the entrance experienced shoreline recession as south-directed sand transport was blocked by the structures and the inlet. The erosion zone was limited to about 2.4 km south of the entrance, at which point shoreline response began to exhibit similar trends to those observed from 1877/83 to 1928 with overall fluctuations in erosion and deposition being slightly greater (Figure 3-8). Changes at four of the five entrances were similar to those observed in previous years, with deposition to the north and erosion to the south of Sebastian, Fort Pierce, and St. Lucie Inlets.

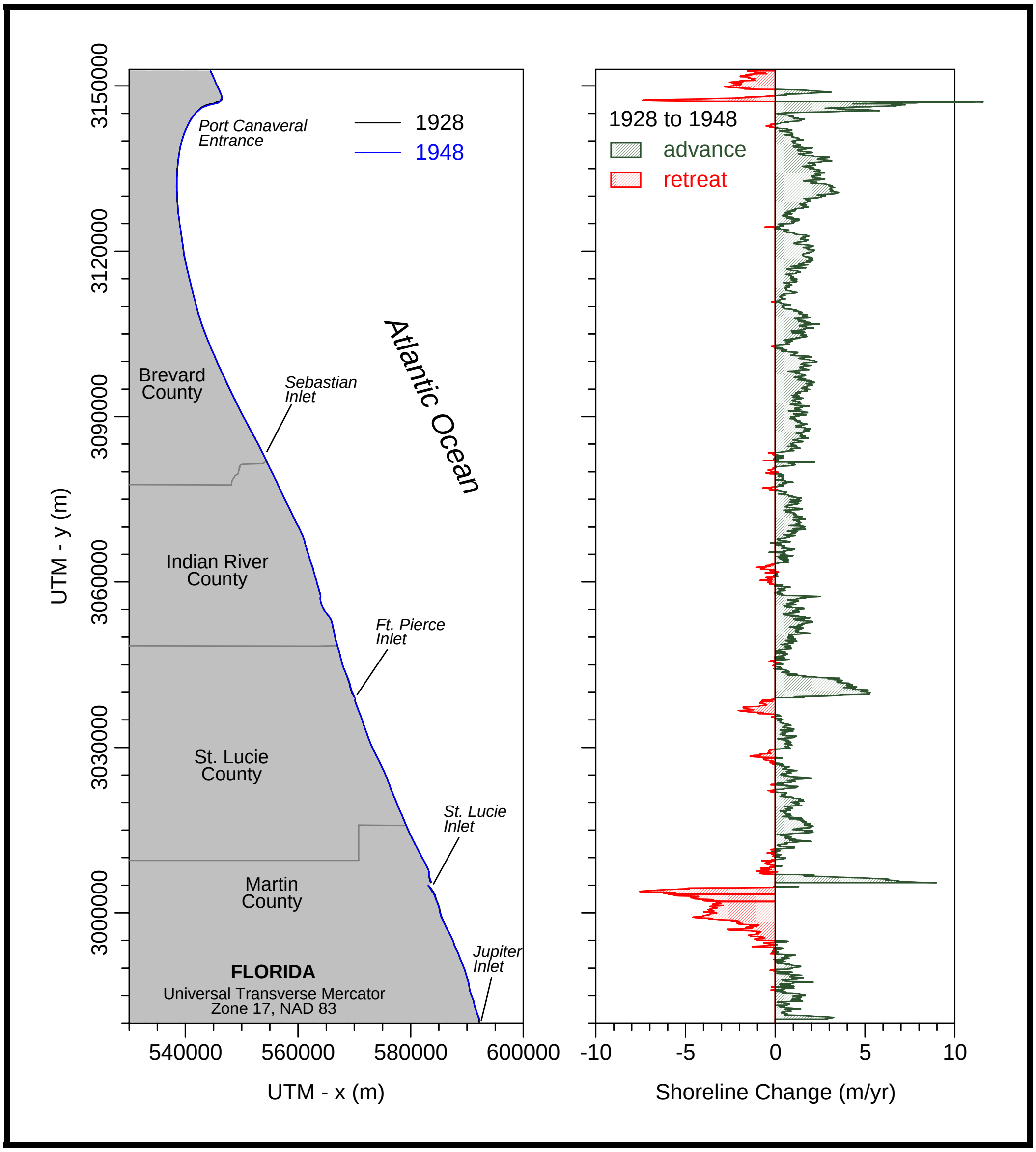

Figure 3-7. Shoreline position and change between False Cape and Jupiter Inlet, FL, 1928 to 1948.

Erosion south of St. Lucie Inlet continued to be a major trend in shoreline response during this time, with recession being dominant from the south side of the entrance to the southern limit of the study area. The maximum erosion rate south of St. Lucie Inlet was approximately 9.5 m/yr, located about 2.4 km south of the entrance.

3.1.3.4 Cumulative Shoreline Position Change (1877/83 to 1970)

Net shoreline change between 1877/83 and 1970 was used to document long-term trends within the study area. The 1877/83 shoreline provided a good baseline for evaluating shoreline change because it represented a time period before the introduction of engineering activities at each of the entrances (i.e., jetty construction, channel dredging, and placement of sand traps). The 1970 shoreline was a good terminal year for long-term comparison because it was the most recent time period that preceded many of the major beach nourishment projects that began to take place in the early 1970s and continue today (see Figure 3-3). As such, shoreline response between these two time periods documented long-term trends that reflect overall patterns of regional change that would be expected to continue in the absence of beach nourishment.

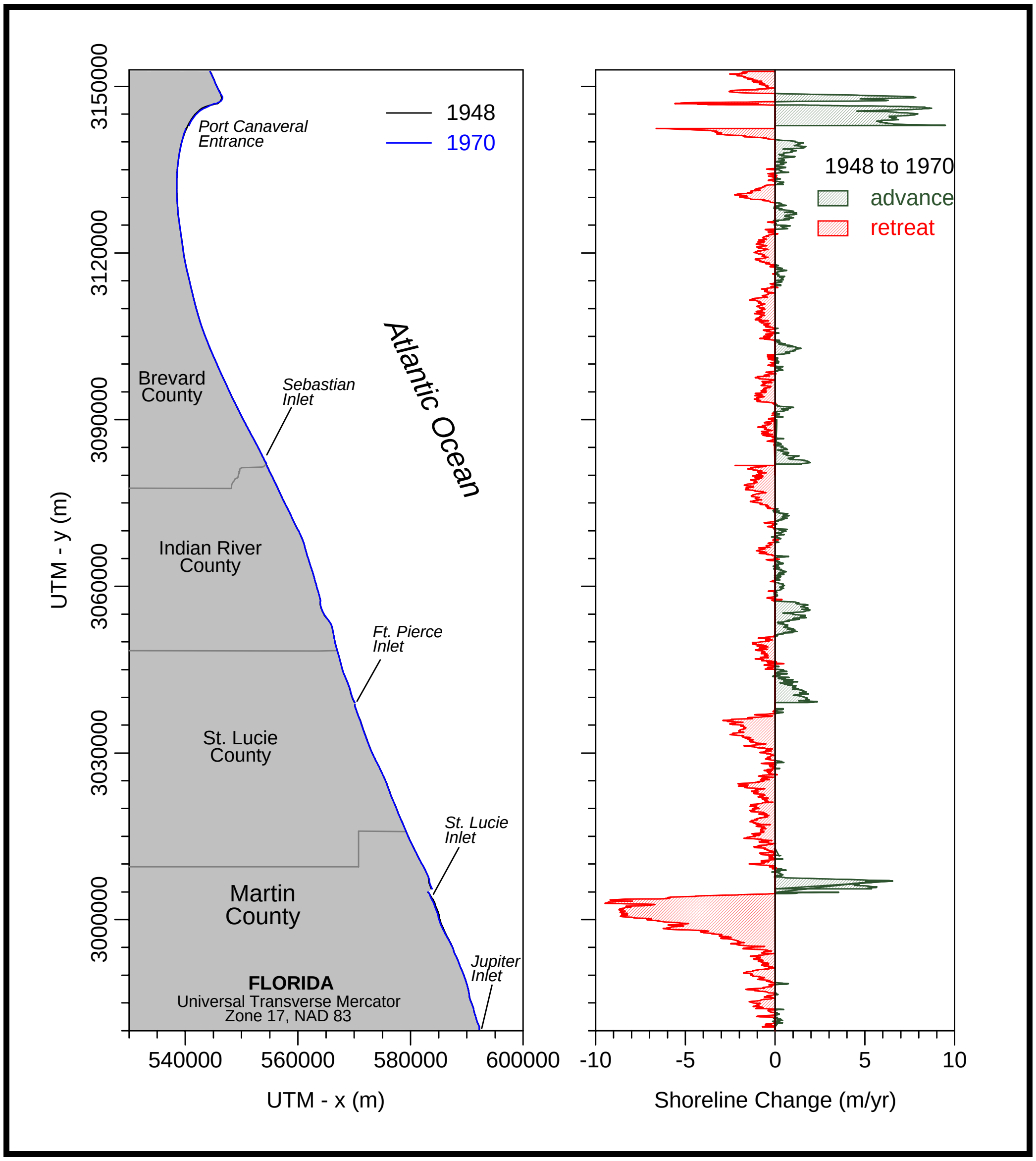

Figure 3-8. Shoreline position and change between False Cape and Jupiter Inlet, FL, 1948 to 1970.

Change trends between 1877/83 and 1970 documented similar erosion and deposition patterns as those observed within the intervening years. Overall, patterns of shoreline advance and retreat were greatest adjacent to entrances (Figure 3-9). This result was consistent with critical erosion areas identified by the FDEP (Figure 3-3). While the overall rate of change was smaller than that observed during shorter time intervals, zones of greatest advance and retreat within the study area continued to be located north of Port

Canaveral and south of St. Lucie Inlet, respectively. Deposition rates of about 5.6 m/yr were recorded north of Port Canaveral while erosion rates of about 9.4 m/yr were recorded south of St. Lucie Inlet. The pattern of change observed south of Port Canaveral between 1948 and 1970 is only visible as a reduction in accretion immediately south of the Port between 1878/83 and 1970, followed by a consistent region of deposition for about 16 km south of the entrance. Shoreline response was relatively stable south of this point until Sebastian Inlet, where the entrance is flanked to the north by deposition and to the south by erosion (Figure 3-9). South of the erosional zone, the shoreline was primarily stable to accretional until south of Fort Pierce Inlet, where the shoreline illustrated net recession for all but a distance of 2.4 km north of St. Lucie Inlet. St. Lucie Inlet is marked by the same north-side deposition and south-side erosion patterns as other entrances, but the magnitude of change was substantially greater for downdrift erosion than at inlets to the north.

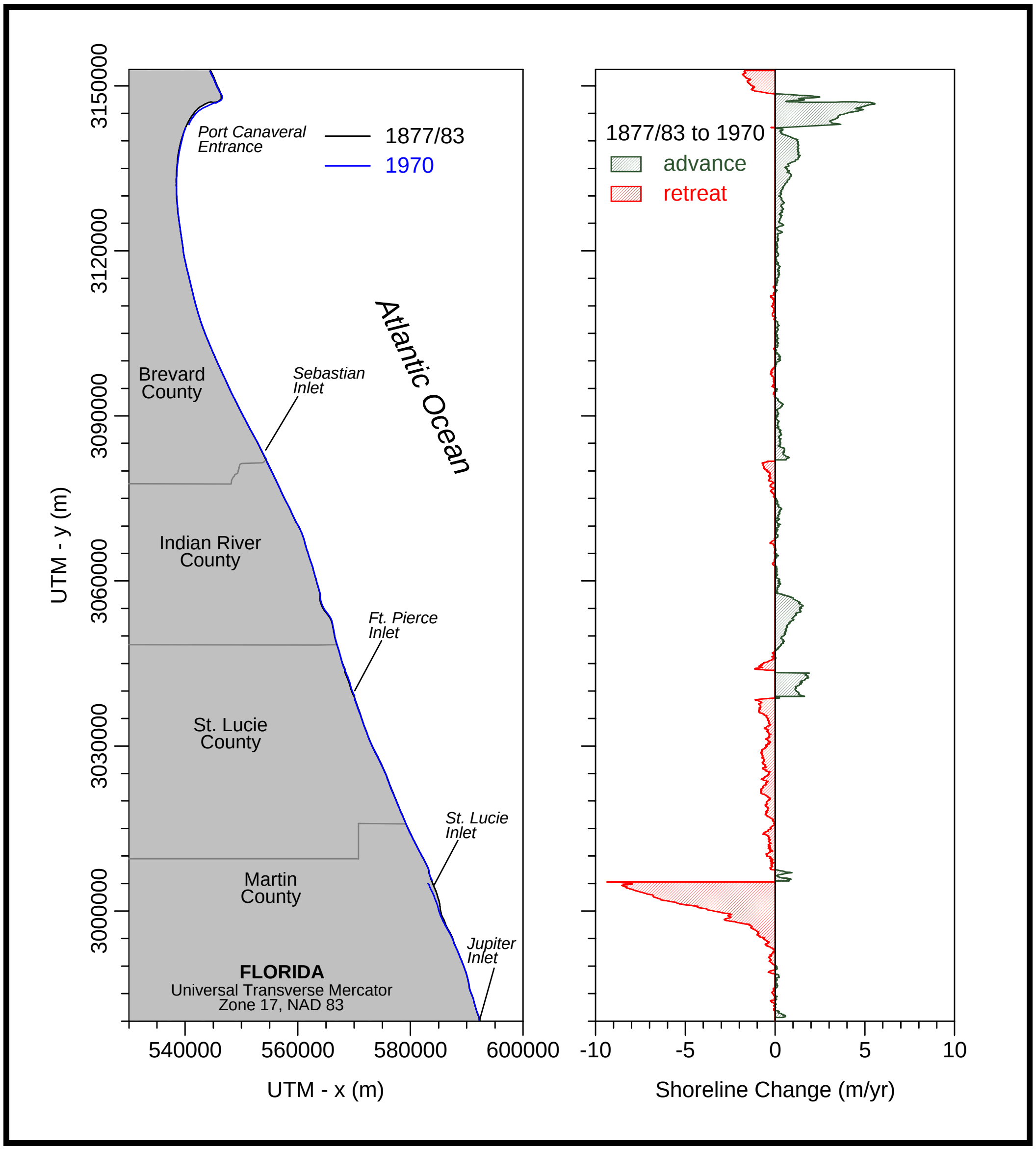

Figure 3-9. Shoreline position and change between False Cape and Jupiter Inlet, FL, 1877/83 to 1970.

3.1.3.5 Recent Shoreline Position Change (1970 to 1996/2002)

The period 1970 to 1996/2002 represents the most recent time interval for quantifying shoreline change, when aerial photography and DGPS surveys were used for recording shoreline position, and beach nourishment was active (see Figure 3-3). This time period was analyzed to identify recent trends in shoreline response to beach nourishment activities and inlet management practices, in addition to natural processes. Locations and volumes of beach fills during this time period (totaling about 21.4 mcm [28 million cubic yards (mcy)] over the total study area) have been included in this analysis to assess factors contributing to change patterns. Trends observed were compared against regions classified as "critically eroding" by the FDEP in 2000 (Figure 3-4). In addition, the effects of using new mapping techniques (e.g., DGPS surveys, improved aerial photo quality, more precise registration methods, and better interpretation techniques) have been taken into consideration. While improvements in shoreline mapping contribute to better quality data sets and potentially more accurate change assessments, comparisons against earlier data sets must consider respective error analyses.

Regional shoreline change trends for 1970 to 1996/2002 are consistent with those observed in previous years. In particular, beaches along the north and south coast of Cape Canaveral showed similar trends of alternating erosion and deposition. Additionally, changes adjacent to four of the inlets illustrated expected erosion and accretion patterns, excluding St. Lucie Inlet, which experienced deposition south of the entrance for the first time. This is particularly important because previous evaluations showed maximum loss for the entire study area along beaches south of St. Lucie entrance. In addition to this shift in trend, some areas that had been experiencing erosion during earlier time intervals and are classified by the FDEP as "critical erosion zones" exhibited deposition during this time interval. Many of these anomalous regions correspond to beach fill areas.

Shoreline change north of Port Canaveral ranged from -5.5 to 7.2 m/yr for this time period. This range is similar to rates observed during previous time intervals, indicating that transport processes in this region remained consistent with long-term trends. South of Port Canaveral, shoreline response was dominated by deposition for a distance of about 13 km, with rates at a maximum of about 4.5 m/yr near the entrance and decreasing gradually to the south. While this trend is consistent with long-term trends observed from 1878/83 to 1970 (Figure 3-9), it deviates significantly from that observed for 1948 to 1970 (preceding short-term interval). Shoreline change from 1948 to 1970 in this region was dominated by recession for about 2.4 km south of the entrance. This change in trend is due in part to beach fills placed south of Port Canaveral. Between 1972 and 2001, approximately 6 mcm (7.8 mcy) of sand was placed along these beaches. Most recently, a beach fill in 2001 covered an area of about 13 km from R-5 to R-50 and consisted of 2.1 mcm (2.8 mcy) of sand. The extent of this beach fill encompassed the entire region of deposition shown in the 1970 to 2002 comparison (Figure 3-10). The trend reversal from the 1948 to 1970 comparison has been influenced by the 1974/75 beach fill and the most recent beach fill. This section of shoreline is part of a 40-km length of shoreline south of Port Canaveral that is considered "critically eroding."

South of Patrick Air Force Base (AFB), shoreline change was dominated by erosion for a distance of about 21 km. Erosion rates in this area were as large as 1.2 m/yr, with an average rate of about 0.5 m/yr. Erosion was more prominent during this time interval than in previous years. Long-term trends document a relatively stable shoreline, with alternating areas of erosion and accretion. Beach fills between 1980 and 2001 were completed along a

6.5-km length of coast at Patrick AFB (R-58 to R-75), totaling 0.9 mcm (1.17 mcy). The most recent fill in 2001, consisting of 414,000 m^3 (541,000 cy) of sand, does not seem to have affected net shoreline change rates significantly. South of this region for about 5 km, shoreline advance was dominant. This deposition zone is associated with the Indialantic beach fill, which was replenished with a total of 1.58 mcm (2.06 mcy) between 1981 and 2002. Of this quantity, 1.03 mcm (1.35 mcy) was placed on the beach during 2002. The effects of the 2002 beach fill are visible along this section of shoreline, as the fill extent parallels that of the deposition zone (Figure 3-10). From this point south to Sebastian Inlet, shoreline recession averages about 0.6 m/yr, which is generally consistent with previous time intervals.

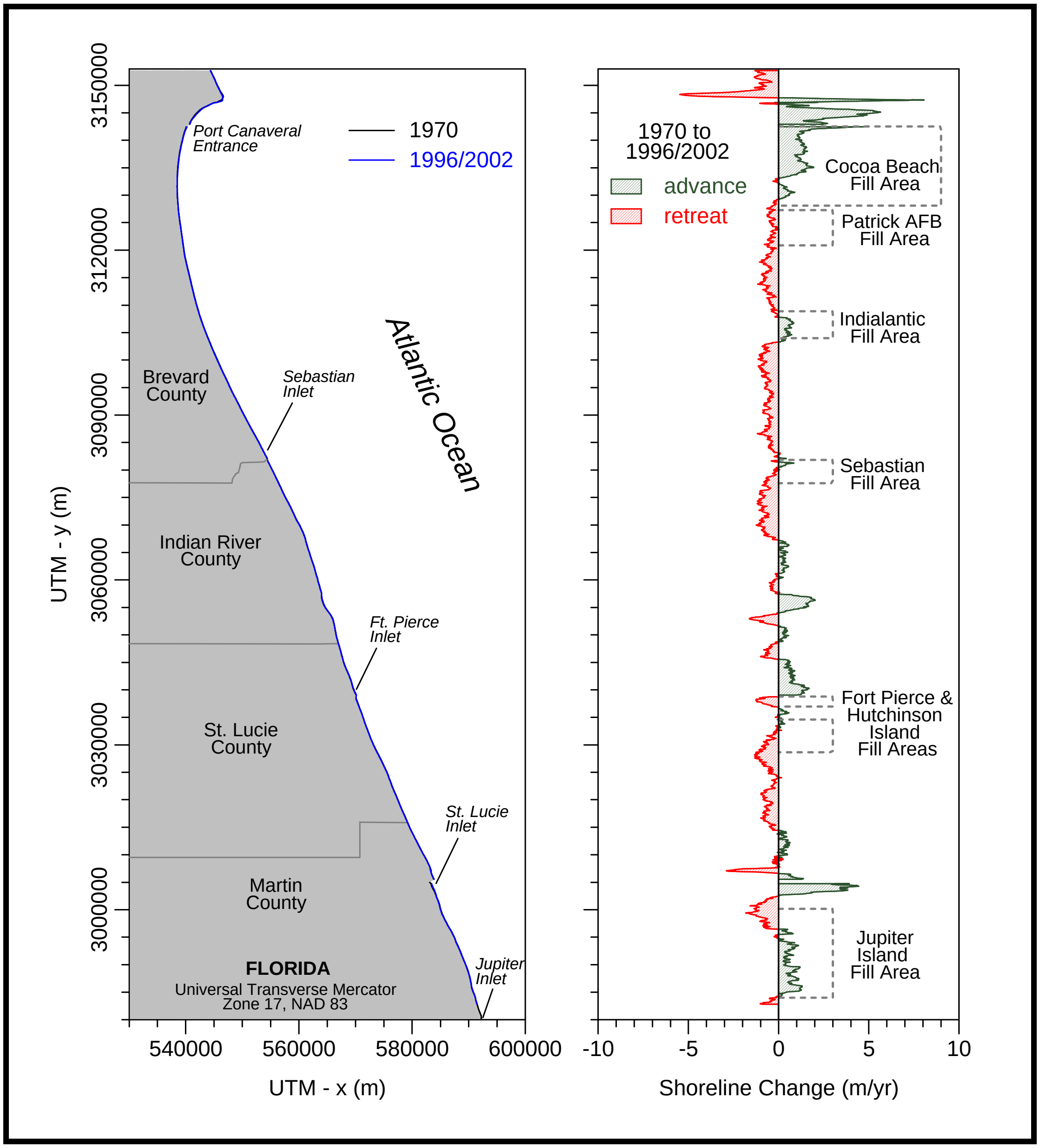

Figure 3-10. Shoreline position and change between False Cape and Jupiter Inlet, FL, 1970 to 1996/2002.

The shoreline immediately south of Sebastian Inlet is primarily erosive for about 16 km, with a small region of deposition immediately south of the entrance. Beach fill activity was conducted south of Sebastian Inlet from 1972 to 1990, totaling about 0.9 mcm (1.17 mcy). The beach fill likely contributed to the small region of deposition that deviates from prior trends. From this point south to Fort Pierce Inlet, shoreline change shows large variability, with moderate rates of erosion and accretion alternating between -1.5 and 2.0 m/yr. Historical trends document similar variability in change patterns along this 45-km section of shoreline. South of Fort Pierce Inlet to St. Lucie Inlet, shoreline recession is dominant, with a minor zone of deposition located approximately 2.3 km south of the entrance. This 3.9-km zone is located immediately south of the Fort Pierce beach fill that was actively nourished from 1971 to 1995. Total beach fill volume during this time period was about 1.45 mcm (1.9 mcy). Southward transport of beach fill likely influenced deposition rates observed in this region.

At St. Lucie Inlet and south along Jupiter Island, shoreline change trends deviate significantly from previous observations. Historically, change along Jupiter Island was dominated by erosion, with minor deposition throughout the region. Although much of the shoreline along Jupiter Island is classified as critically eroding, change trends for the recent time interval illustrate only a small erosional zone south of the inlet for a distance of about 6.4 km. Most of the shoreline illustrates accretion. There are two primary reasons for this trend reversal. The first is associated with construction of the south jetty at St. Lucie Inlet between 1980 and 1982 (Figure 3-11). Subsequent to construction of the south jetty, it seems that erosion trends were abated. Second, beach nourishment projects along Jupiter Island between 1970 and 2002 were quite extensive, including an active 2002 beach fill that is visible in aerial photos used to delineate the shoreline in this region. Total fill volume placed in this region between 1970 and 1996 (excluding the 2002 fill) was about 8.6 mcm (11.3 mcy). Both factors contributed heavily to the significant alteration in shoreline change trends for this time period.

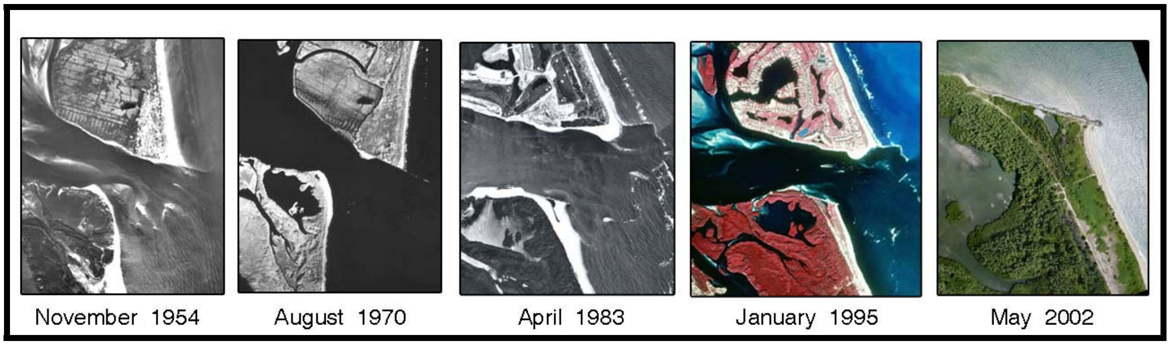

Figure 3-11. Recent shoreline evolution at St. Lucie Inlet, 1954 to 2002.

3.2 NEARSHORE BATHYMETRIC CHANGE

3.2.1 Bathymetric 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. Five data sets were compiled to document shelf characteristics and examine temporal changes between 1878/83 and 1996. Four data sets were developed from USC&GS Hydrographic surveys (H-sheets), including 1878/83, 1929/30, 1956, and 1964/73. The fifth survey was conducted by the USACE in

1996, and was limited to the offshore region north of Port Canaveral over Canaveral Shoals. Bathymetric surfaces were developed for these time periods to characterize morphologic characteristics of the continental shelf in this region, and change calculations were performed to determine potential infilling rates at each of the borrow sites. Regional temporal comparisons were made for a 200-km coastal segment from the north side of Cape Canaveral (about 16 km north of the tip of Cape Canaveral) to Jupiter Island (about 1.6 km north of Jupiter Inlet), extending offshore to about the 40-m depth contour in the north and to about the 90-m depth contour in the south (southern depths being significantly deeper due to narrowing of the east coast shelf from north to south in this section of Florida [Figure 3-11). Because data density for both time periods decreases with distance offshore, data extents were clipped to areas with the best survey coverage (between 13 and 19 km offshore). The survey sets consist of digital data compiled by the National Geophysical Data Center (NGDC) and analog information (scanned H-sheets) compiled at Applied Coastal using standard image registration and digitizing procedures (Byrnes and Baker, 2003). All data were registered to a common horizontal coordinate system and datum, in this case UTM Zone 17 North and NAD83.

The first regional USC&GS bathymetric survey was conducted in 1878/83 (Table 3-5). Nearshore surveys were mapped at scales of 1:20,000, whereas offshore surveys focused on regional data coverage at a scale of 1:40,000. The density of points in the 1878/83 data set was adequate for describing historical bathymetric features and characterizing coastal and shelf topography, however, more recent surveys (1929/31,1956, 1964/73, and 1996) recorded many more points for describing surface characteristics in sub-sections of the overall area. As such, all quantitative volume change calculations within the borrow sites were made based on data from the 1930/31, 1956, 1964/73, and 1996 surfaces. All change calculations were made using the best available survey data for each site (i.e., greatest point density, most recent time period). Digital data for 1930/31, 1954, and 1964/73 bathymetry are available from the NGDC.

Table 3-5. Bathymetric source data characteristics summary.

Date	Data Source	Comments and Map Numbers
1878/83	USC&GS H-sheets	1878 - Mosquito Inlet to False Cape (H-1409, 1:40,000) 1878/91 - False Cape to Canaveral Shoals (H-1410 1:20,000). 1878 -Cape Canaveral Shoals (H-1411a, 1:20,000). 1881 -Southeast Shoal off of Cape Canaveral (H-1411b, 1:20,000). 1881 -Port Canaveral to Sebastian Inlet (H-1488a, 1:40,000). 1881 -Sebastian Inlet to (H-1488b, 1:40,000). 1882/83 - (H-1523a, 1:40,000). 1882/83 - to Jupiter Inlet (H-1523b, 1:40,000).
1929/31	USC&GS H-sheets	1930 -H-5025 (1:5,000), H-5023(1:10,000:), H-5022, H-5026, H-5027, H-5028, H-5040 (1:20,000), H-5032, H-5034, H-5057, H-5047, H-5116 (1:40,000), H-5029 (1:80,000) 1931 -H-5031 (1:20,000), H-5120 (1:40,000).
1956	USC&GS H-sheets	H-8340 (1:10,000), H-8341, H-8342, H-8343, H-8344 (1:20,000), H-8345 (1:40,000).
1964/73	USC&GS H-sheets	1964 - H-08783 (1:100,000). 1965 - H-8840, H-8839 (1:80,000). 1967 - H-8955, H-8957 (1:20,000). 1973 - H-9344 (1:40,000).
1996	USACE Survey	Digital data provided by the USACE.

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 included 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. Depths were adjusted to the North American Vertical Datum (NAVD) of 1988 and were projected to average sea level for the most recent survey. 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.

To produce continuous surfaces extending seaward from the high-water line, all bathymetric data were combined with temporally consistent shoreline data. An elevation of 2.1 m (NAVD) was assigned to the shoreline based on recent beach profile data obtained from the FDEP and tidal datum reference elevations provided by NGS for stations at Sebastian (8722004) and Fort Pierce (8722212) Inlets. A plot illustrating beach profile examples for 2002 in Brevard County portrays the typical beach shape observed in this region with an identifiable berm crest at elevations ranging from 2.0 to 2.4 m NAVD (Figure 3-12).

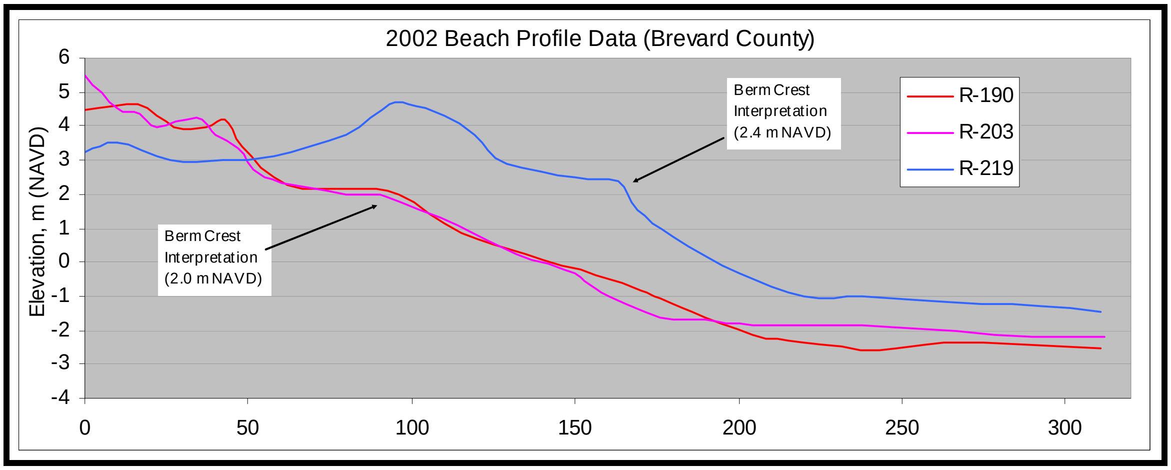

Figure 3-12. Beach profile shape at transects R-190, R-203, and R-219 in southern Brevard County.

As with shoreline data, measurements of seafloor elevation contain inherent uncertainties associated with data acquisition and compilation. It is important to quantify limitations in survey measurements and document potential systematic errors that can be eliminated during quality control procedures. However, most measurement errors associated with present and past surveys are considered random over large areas. As such, random errors cancel relative to change calculations derived from two surfaces. A better method for determining limits of reliability for erosion and accretion areas is to quantify measurement uncertainty associated with bathymetric surfaces. Interpolation between measured points always includes a degree of uncertainty associated with terrain irregularity and data density. The density of bathymetric data, survey line orientation, and magnitude and frequency of terrain irregularities are the most important factors influencing uncertainties in volume change calculations between two bathymetric surfaces (Byrnes et al., 2002). Volume uncertainty relative to terrain irregularities and data density can be determined by comparing surface characteristics at adjacent survey lines. Large variations in depth between survey lines (i.e., few data points describing variable bathymetry) will result in large uncertainties between lines. The computation provides a best estimate of uncertainty for gauging the significance of volume change calculations between two surfaces.

Uncertainty estimates were calculated for the 1878/83, 1929/31, 1956, 1964/73, and 1996 bathymetric surfaces using methods outlined in Byrnes et al. (2002). Multiple sets of line pairs were compared for each time period to represent terrain variability across the surveyed area. Line pairs were chosen that would accurately reflect track line spacing for each survey and the irregularity of prominent geomorphic features in the region. An example of line pairs used for the 1929/31 surface is displayed in Figure 3-13. Lines were established for each time period to overlay survey lines for that year. Bathymetric data were extracted along each line to calculate the variation in elevation between line pairs. Depths were computed at five meter intervals along each line and the absolute values of the differences were averaged to calculate the potential uncertainty for each pair.

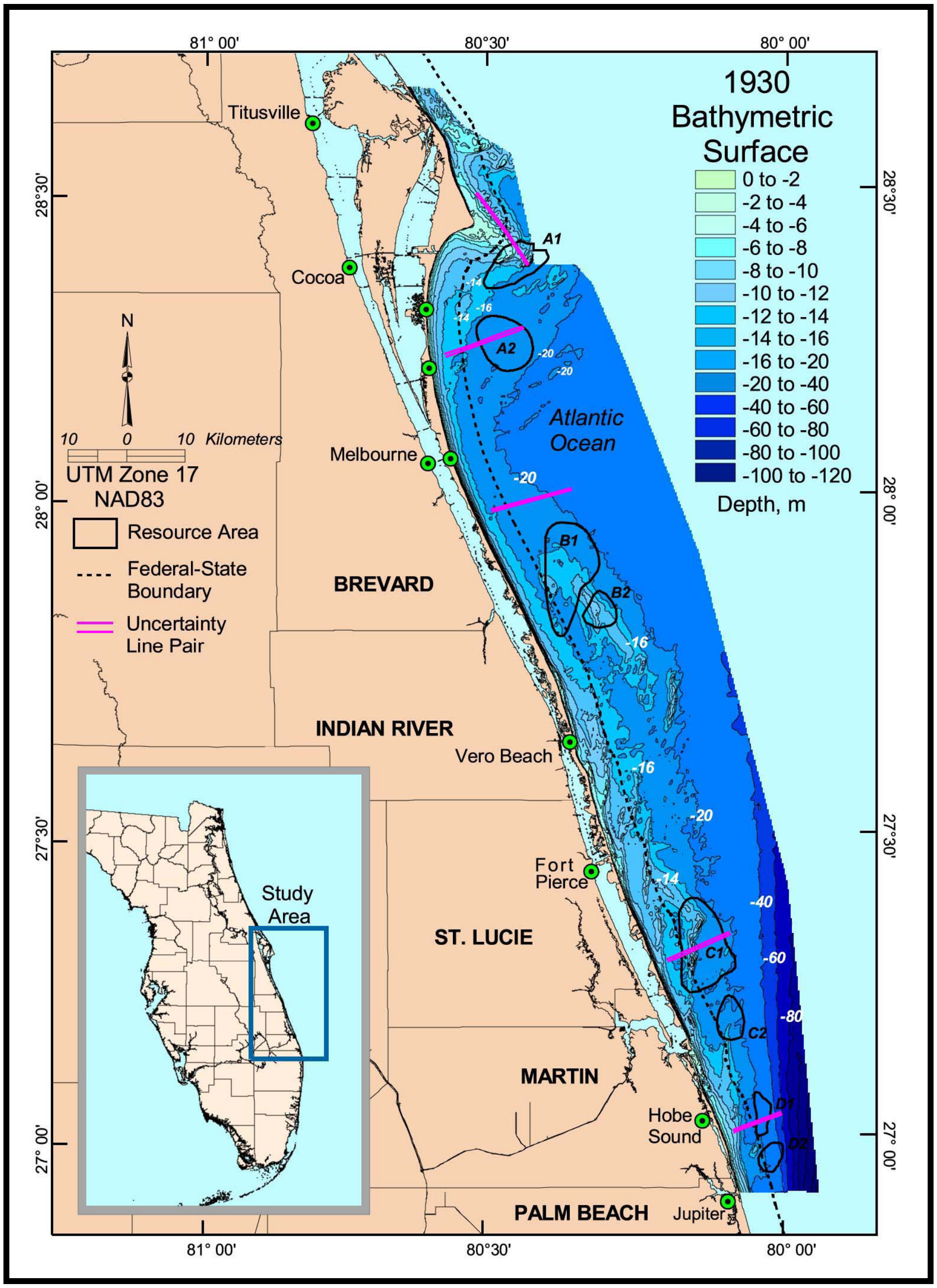

Figure 3-13. Line pairs used to calculate uncertainty for the 1929/31 bathymetric surface.

Results of uncertainty calculations are summarized in Table 3-6. In general, potential uncertainty decreased with time. This was expected due to increases in survey line spacing and better orientation through time. The 0.1 m increase in uncertainty from 1964/73 to 1996 is because most of the 1996 surface encompasses the irregular topography of Canaveral Shoals. As such, an increase in variability for this time period is expected. Combining this information to gauge the impact of potential uncertainties associated with volume change calculations derived from these surfaces resulted in a root-mean-square variation of ± 0.4 m for the 1930/31 to 1964/67 change surface and ±0.4 m for the 1956 to 1996 change surface. For all bathymetric change calculations used for this study, a value range of 0.4 to -0.4 m was used to delineate areas of no determinable change.

Table 3-6. Bathymetric uncertainty estimates.

Data Set	1878/83	1929/31	1956	1964/73	1996
Average Uncertainty (m)	±0.4	±0.3	±0.2	±0.2	±0.3
RMS Error for Change Surfaces					
Data Set	1929/31 to 1964/73			1956 to 1996	
RMS Error (m)	±0.4			±0.4	

3.2.2 Digital Surface Models

Historical bathymetric data 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 for conducting this analysis is to document net sediment transport trends on the shelf surface and to quantify the magnitude of change to verify 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 at sand borrow sites.

3.2.2.1 1877/83 Bathymetric Surface

Bathymetric data for the period 1878/83 were combined with the 1877/83 shoreline data to create a continuous surface from the high-water shoreline seaward to about the 40-m (NAVD) depth contour. The study area is well defined by the shape of the continental shelf as it narrows from a maximum width of about 48 km just south of Cape Canaveral to a minimum of about 16 km near Jupiter Inlet. As the shelf merges with the north-south oriented Florida-Hatteras Slope, shelf gradient increases noticeably from north to south. Meisburger and Duane (1971) characterized the continental shelf in this region as consisting of three major components, including the inner shoreface zone, the inner shelf plain, and the outer shelf plain. Major characteristics of two of the three shelf regions are visible in the 1878/83 bathymetric surface (Figure 3-14). The narrow shoreface zone extends offshore from the high-water line to about the 10-m depth contour, seaward of which the shelf flattens into the gently sloping inner shelf plain with depths between about 10 and 16 m. East of the inner shelf plain, the seafloor becomes more steeply sloping and irregular as the outer shelf transitions to the top of the Florida-Hatteras Slope. Due to the limited offshore extent of the 1878/83 data set, much of the outer shelf plain is not visible in the 1878/83 bathymetric surface.

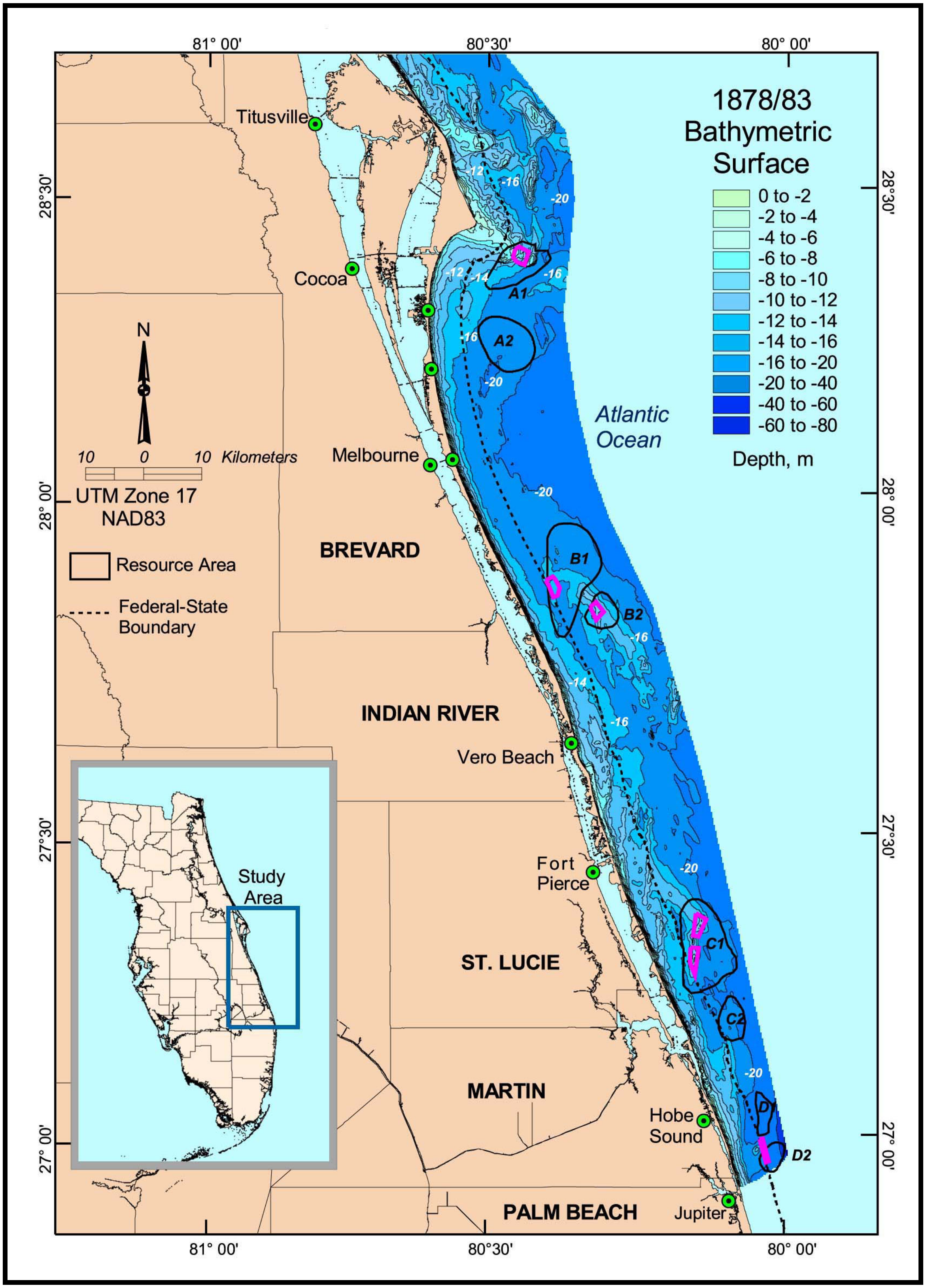

Figure 3-14. Nearshore bathymetry (1878/83) for offshore Florida.

The most prominent geomorphic features throughout the region are offshore shoals and linear sand ridges, from Ohio-Hetzel and Chester Shoals in the north to Gilbert Shoal in the southern portion of the study area (see Figure 3-1). Most of the linear shoals are oriented in a north-south alignment and are most extensive along the inner shelf near Cape Canaveral, Fort Pierce Inlet, and St. Lucie Inlet. Most shoals in the study area are located about 12 to 14 km offshore, landward of the 20-m depth contour, and range in depth from about 8 to 14 m. Bethel Shoal is located farther offshore, at a distance of about 18 km. Many of the shoals visible on the 1878/83 surface exist seaward of the Federal-State Boundary, creating ideal locations for potential sand borrow sites for beach nourishment.

A number of shore-attached ridges have been documented adjacent to the present-day location of Fort Pierce Inlet (Figure 3-14; McLaren and Hill, 2002). While none of the present-day inlets were naturally open to the Atlantic Ocean in their current positions during the 1877/83 shoreline survey, a naturally occurring opening north of the present-day location of Fort Pierce Inlet was evident in the 1877/83 and an earlier 1860s shoreline survey, which may have had influence on the formation of shore-attached sand ridges and shoals within this region (McBride and Moslow, 1991).

The morphology of the continental shelf varies considerably from north to south. Adjacent to Cape Canaveral, topography is highly irregular, with large shoals extending southeast from False Cape and Cape Canaveral (Figure 3-15). Large shoals, ridges, and channels exist along the shelf surface adjacent to the Cape from the shoreface to about 12 km offshore. The alignment of ridges paralleling the Cape shoreline and extending southeast from the foreland is indicative of littoral processes controlling the formation of these features. Sediment eroded from northern beaches is transported southeast into the ridge-shoal complex, creating linear features that migrate in a step-wise fashion to the south and east, creating a highly irregular inner shelf surface. The shoal system extending from Cape Canaveral is generally very shallow, with depths ranging from about 3 to 12 m.

South of the Canaveral shoal system, shelf topography becomes more subdued as it flattens toward Canaveral Bight (Figure 3-15). Much of the study area between Port Canaveral and Sebastian Inlet is primarily flat, lacking the variable topography present for the shoal complex to the north. Shelf orientation parallels the shoreline in this region and generally deepens from a depth of about 12 m at the shoreface to about 40 m over a distance of about 23 km. From Sebastian Inlet to Jupiter Inlet, shelf morphology again becomes more irregular, with numerous north-south trending shoals dominating the structure of the shoreface and the inner shelf (Figure 3-16).

Most sand resource areas identified for this study are associated with shoals visible on the 1878/83 surface, including Southeast Shoal (A-1), Thomas Shoal (B-1 and B-2), St. Lucie Shoal (C-1), and Gilbert Shoal (C-2). Excluding Thomas Shoal, each of these has been characterized previously by ICONS as containing material suitable for beach fills (Figure 3-17; Meisburger and Duane, 1971; Field and Duane, 1974). Thomas Shoal was not characterized as extensively as other shoals during the ICONS study, however, the suitability of surrounding shoals indicates that this shoal would likely be a good candidate as a borrow site as well.

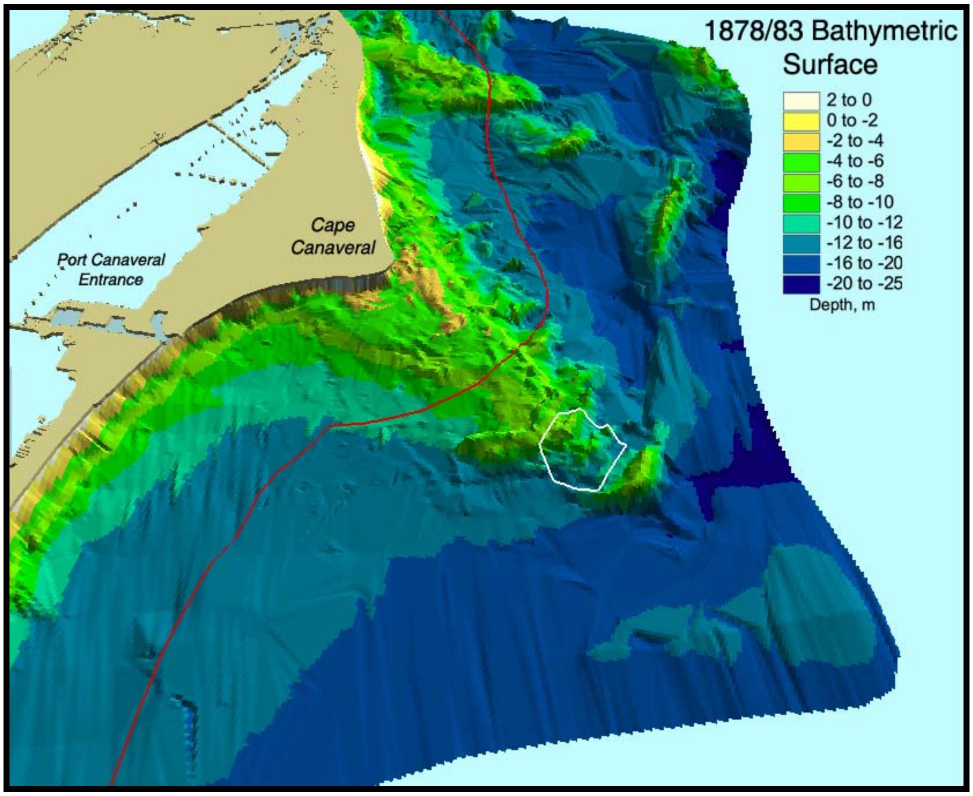

Figure 3-15. Three-dimensional view of Canaveral Shoals, 1878/83.

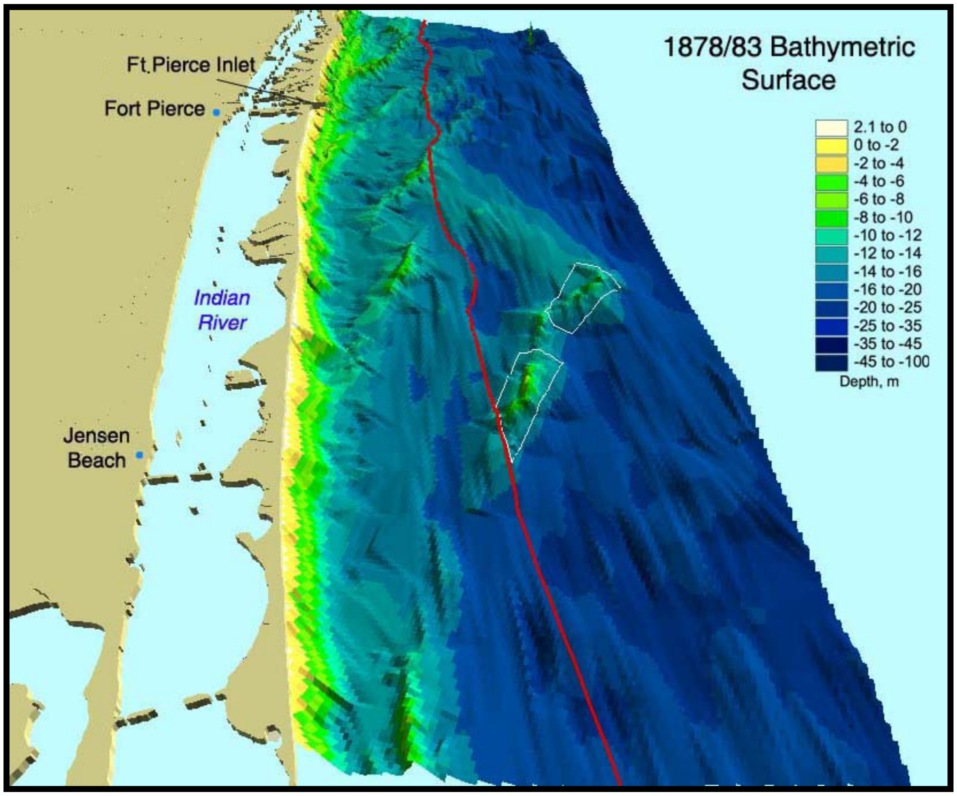

Figure 3-16. Three-dimensional view of shoal field near Ft. Pierce Inlet, 1878/83.

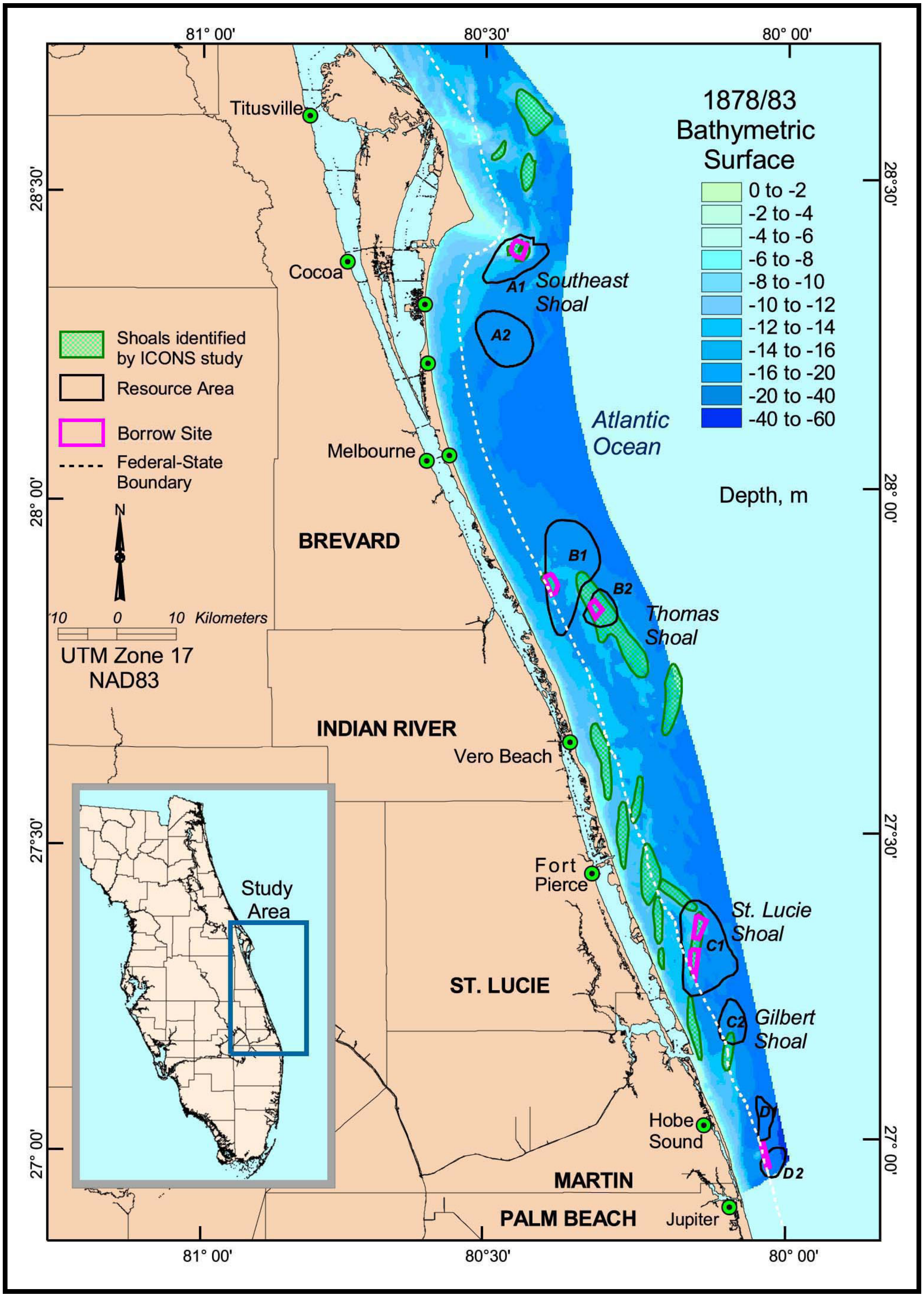

Figure 3-17. Nearshore bathymetry (1878/83) with ICONS shoals identified.

3.2.2.2 1929/73 Bathymetric Surface

Bathymetric data for the years 1929/31, 1956, and 1964/73 were compiled to create a continuous surface representing the most recent time period for regional bathymetric characterization. Most data are composed of the 1956 and 1964/73 data sets, but some regions lacking sufficient data coverage from either of those time periods were filled with data from the 1929/31 surveys to provide complete coverage for the region. Bathymetric data were combined with shoreline data that were temporally coincident with the survey time period abutting the coast. Major characteristics of this bathymetric surface are similar to those of the 1878/83 surface with a couple of exceptions (Figure 3-18). First, the number of data points describing geomorphic features was greater, thus enabling better characterization of the numerous shoals and linear sand ridges. Second, the combination of these data sets allowed for increased data coverage seaward of the 1878/83 data set, providing better characterization of the outer shelf surface.

Overall, general characteristics of the bathymetric surface are similar to those of the previous time period. The shape, size, and position of sand ridges are consistent for both surfaces, with a few changes visible in the 1929/73 bathymetry. First, the shoreface fronting Cape Canaveral displayed some noticeable differences from the previous time period. The shelf surface north of the Cape is visibly steeper along the shoreline, which is consistent with sediment transport and shoreline change trends illustrating long-term erosion for this region (Figure 3-19). Additionally, the area south and east of Cape Canaveral showed noticeable shoaling, indicated by seaward advance of the 4-m depth contour. While the size and shape of the subaqueous spit platform surrounding the Cape remained relatively unchanged, depths over the feature generally decreased. This result is consistent with shoreline change and sediment transport trends, which showed constant deposition on the southern shoreline of the Cape. Additionally, the inner shelf between Port Canaveral and Sebastian Inlet shoaled somewhat during this time period, as bathymetric depressions evident landward of the 20-m depth contour on the 1878/83 surface were significantly diminished on the 1929/73 surface. Seaward of the 20-m depth contour, some bathymetric highs visible on the 1929/73 surface were absent from the 1878/83 surface. This may be due in part to better data coverage, but it is a noticeable change from the previous data set. The southern portion of the study area has noticeable improvements in shoal and ridge definition, which are visible at the shore-attached ridges in the vicinity of Fort Pierce and at offshore shoals (Figure 3-20).

3.2.2.3 1996 Bathymetric Surface

A 1996 bathymetric survey acquired by the USACE was used to characterize recent bathymetry adjacent to Cape Canaveral. Although the extent of this data set was limited to the offshore area north of Port Canaveral, the density of data points provided a good source of additional information for assessing sediment transport patterns in the area. The general characteristics of the seafloor offshore Cape Canaveral were very consistent with those of the 1929/73 data set, with some changes apparent along the shoreline and on the shoreface (Figure 3-21). The shape and size of shoals were very similar to those documented in previous time periods, with some lengthening of linear features throughout the subaqueous spit complex (Figure 3-22). Extension of the terminal point of the Cape was visible at the shoreline, and seaward expansion of the 4-m depth contour was noticeable.

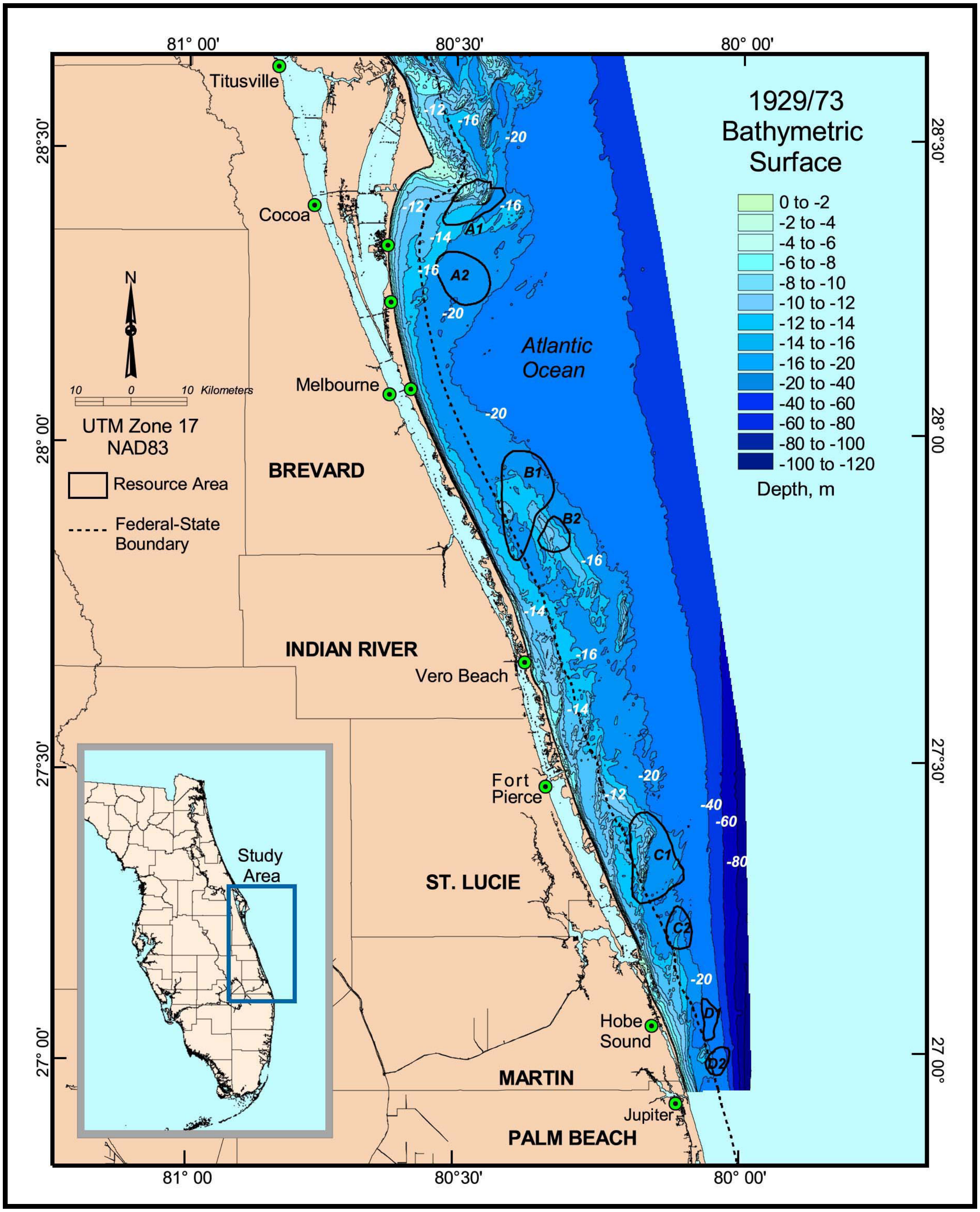

Figure 3-18. Nearshore bathymetry (1929/73) for offshore Florida.

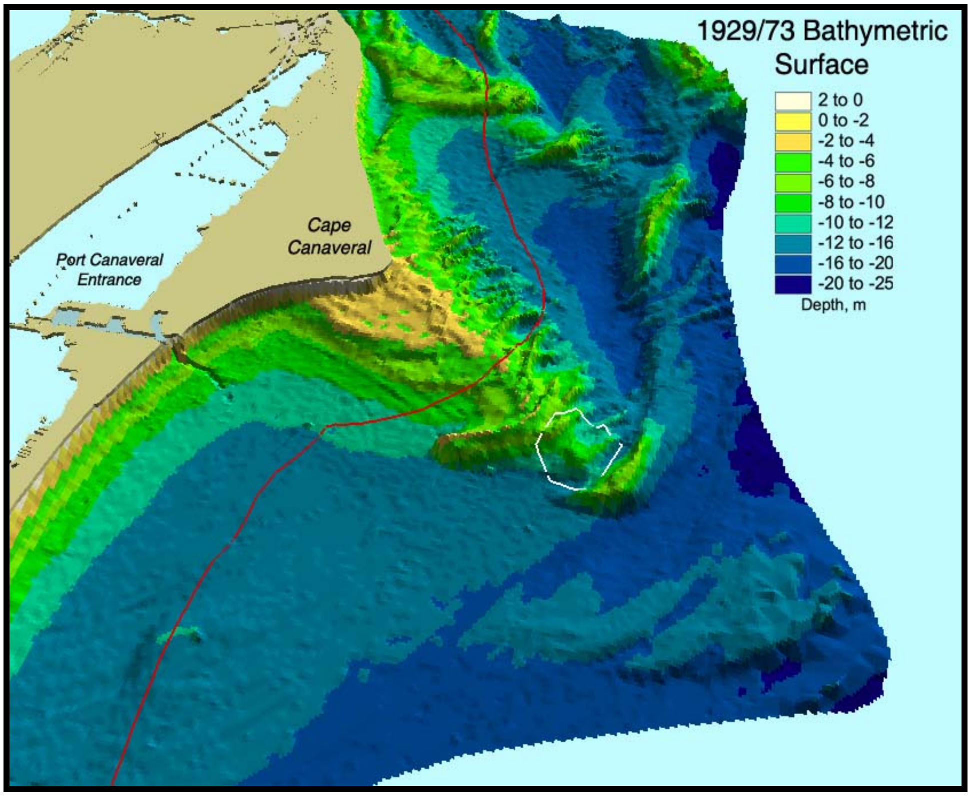

Figure 3-19. Three-dimensional view of Canaveral Shoals, 1929/73.

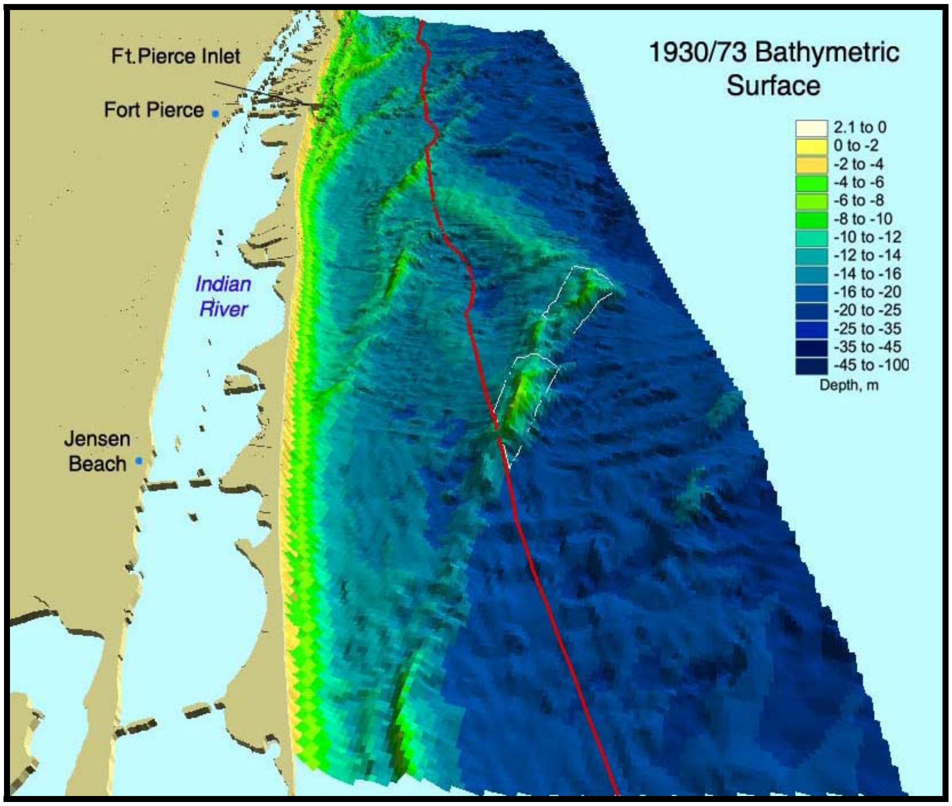

Figure 3-20. Three-dimensional view of shoal field near Ft. Pierce Inlet, 1930/73.

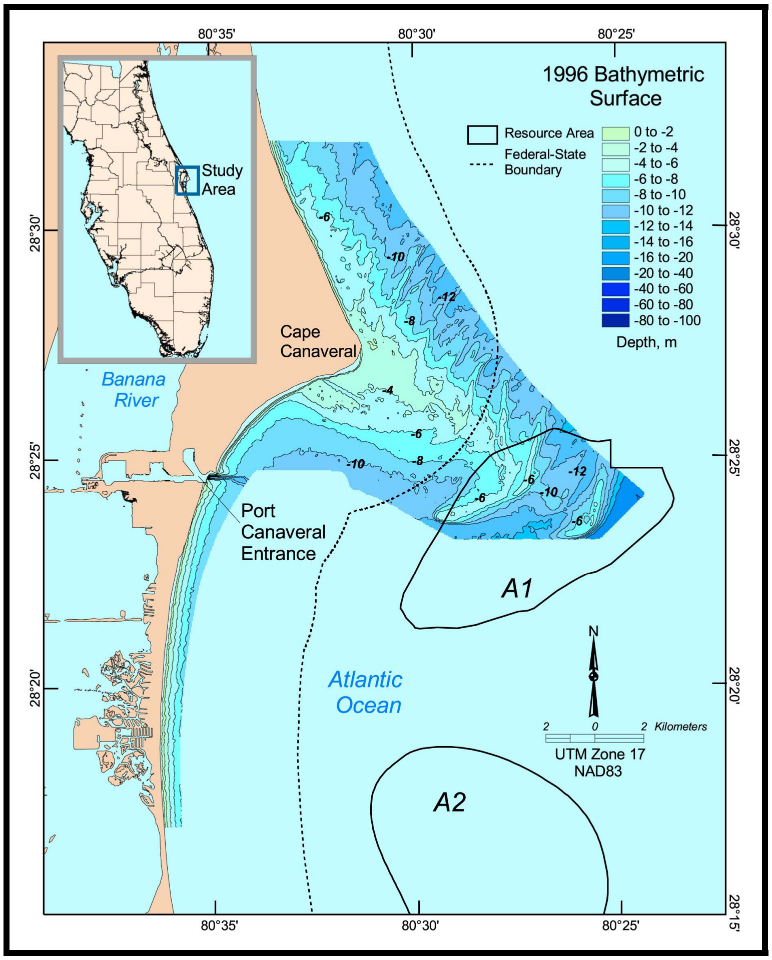

Figure 3-21. Nearshore bathymetry (1996) for offshore Florida.

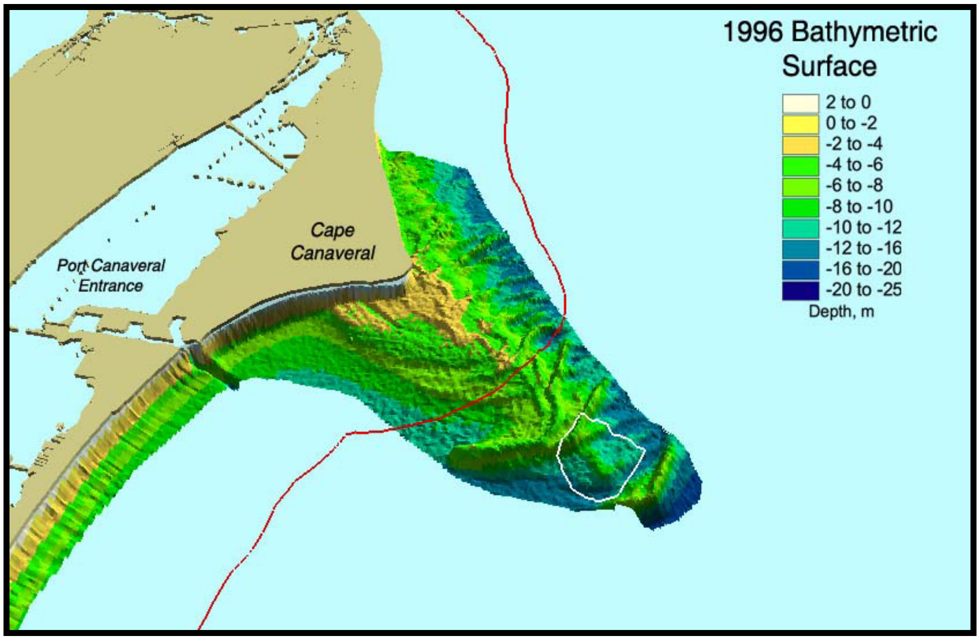

Figure 3-22. Three-dimensional view of Canaveral Shoals, 1996.

3.2.3 Shelf Sediment Transport Dynamics

Although general characteristics of the bathymetric surfaces are similar for 1878/83, 1929/73, and 1996, a digital comparison of these surfaces yielded a difference plot that isolated areas of erosion and accretion for documenting sediment transport patterns and quantifying trends. Due to variation in data coverage at each borrow site, different time periods were used to quantify change trends depending on which data sets were determined to be best for comparison at each site. A comparison between 1956 and 1996 data sets was used for quantifying transport rates at Borrow Site A1, and the 1929/31 and 1964/73 data sets were used for determining rates at Sites B1 through D2. Two regional change plots were generated for the study area. A bathymetric change plot from 1956 to 1996 extended from the northern boundary of the study site to the north side of Port Canaveral (Figure 3-23), and a comparison between 1929/31 and 1929/73 was generated for the offshore area south of Port Canaveral to the southern boundary of the study area (Figure 3-24).

3.2.3.1 Bathymetric Change Adjacent to Cape Canaveral: 1956 to 1996

Bathymetric change observed between 1956 and 1996 along the inner shelf adjacent to Cape Canaveral depicts a high-energy environment within this topographically variable region. South-directed longshore transport around Cape Canaveral mobilizes substantial quantities of sand near the coastline and on the upper shoreface, resulting in subaqueous spit growth along the down-drift margin of the Cape and shoal migration, illustrated as areas of erosion (yellow to red) and deposition (light to dark blue) on Figure 3-23. Polygons of erosion and deposition generally follow contour shapes defined by shoals and troughs. Alternating zones of accretion and erosion reflect the migration of sand ridges. Deposition zones to the southeast of erosion areas indicate dominant south-directed transport processes. Clearly defined linear regions of erosion are flanked to the southeast by large linear deposits, reflecting transport trends under incident wave and current processes. Significant deposition along the beach south of Cape Canaveral indicates high rates of sediment transport from beaches and shoals. Bathymetric change is greatest along the exposed northeast region of the study area, with magnitudes decreasing in the protected southwest region, as wave energy dissipates over Canaveral Shoals. Shelf bathymetry exposed to waves from all directions is more variable than that to the southwest, where low relief features reside within Canaveral Bight. Shelf bathymetry south of Canaveral Shoals and north of Thomas Shoal (Figure 3-19) is relatively featureless, reflecting the protection provided by Canaveral Shoals from east and northeast waves.

Processes observed in the change comparison between the 1956 and 1996 data sets are supported by data developed as part of the Cape Canaveral ICONS study. Using seismic reflection profiles and sediment samples, the study identified active shoal reworking through abrasion and transport in this region. Bottom profile comparisons made for the ICONS study indicate that since 1898, all shoals associated with Cape Canaveral have broadened, thickened, and become shallow. Additionally, shoals landward of the 6-m depth contour have shifted slightly southeast (Field and Duane, 1974), which is consistent with trends observed in Figure 3-23.

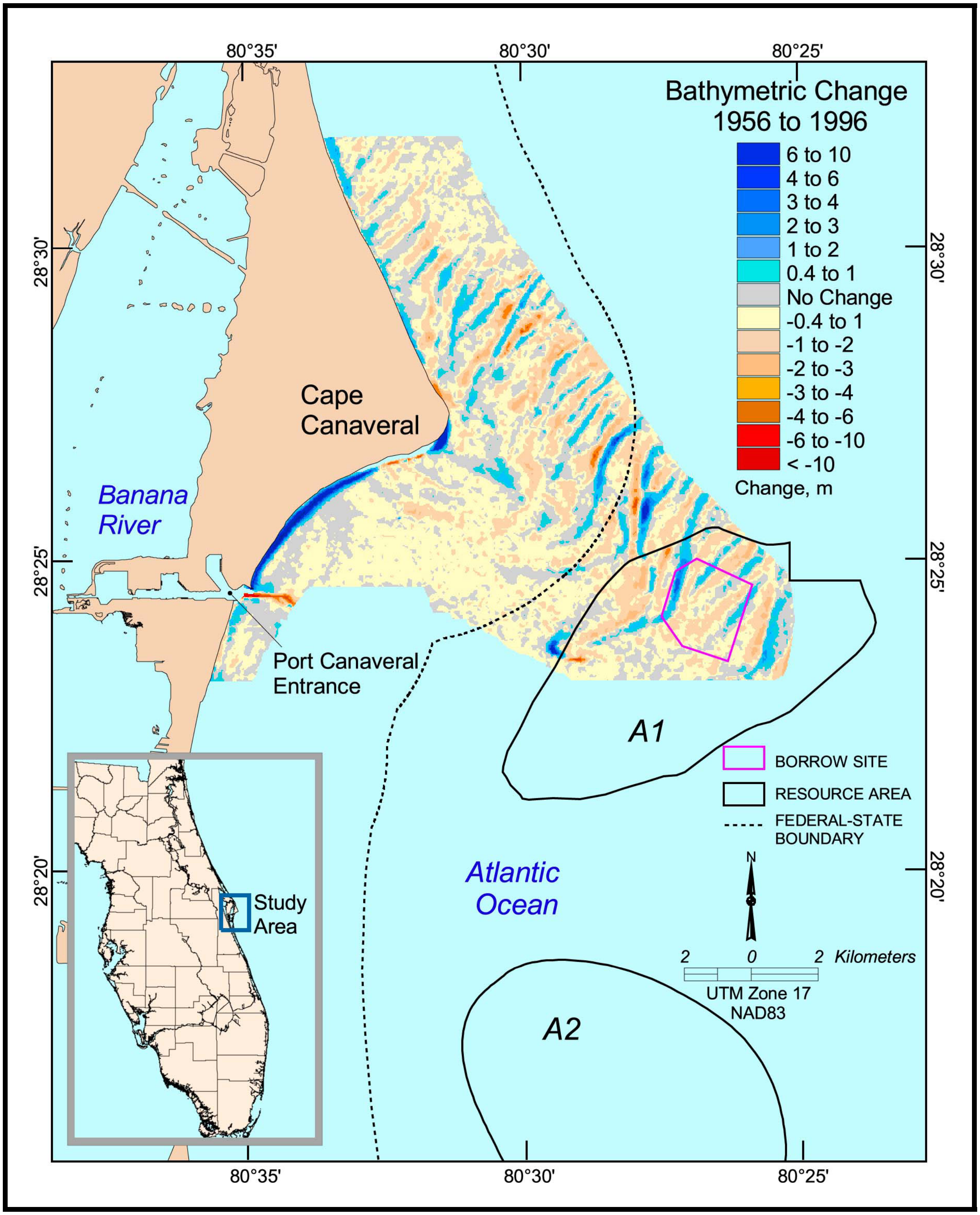

Figure 3-23. Nearshore bathymetric change between 1956 and 1996 for offshore Cape Canaveral.

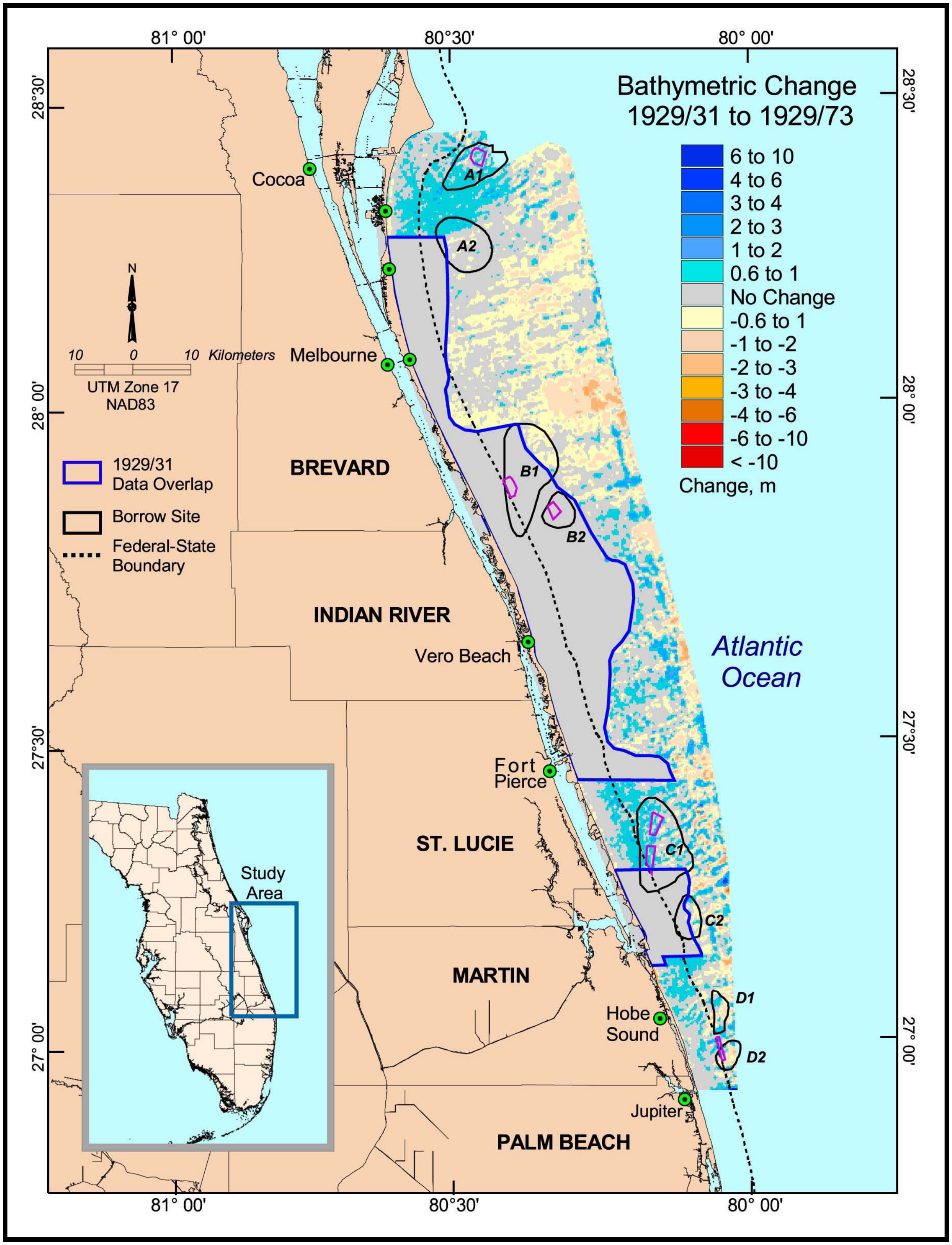

Figure 3-24. Nearshore bathymetric change between 1929/31 and 1929/73 for offshore central east Florida.

The depth over shoals seaward of Cape Canaveral is relatively shallow, representing a viable region for sand resources. Canaveral shoals have been identified by Field and Duane (1974) as suitable sources for beach nourishment projects based on textural similarities with beach sands and thickness of deposits. Samples documented a median grain size along Southeast Shoal (associated with Borrow Site A-1) of 0.31 to 1.12 mm, with a standard deviation of 1.46 to 2.1 mm (Field and Duane, 1974). They estimated that a minimum of 11.6 mcm of sand was highly suitable for beach nourishment.

3.2.3.2 Bathymetric Change South of Port Canaveral: 1929/31 to 1929/73

Transport processes affecting bathymetric change between 1929/31 and 1929/73 south of Port Canaveral diverge from those observed to the north. Wave and current processes driving sedimentation and shoal migration adjacent to Cape Canaveral are reduced for shelf areas south of Port Canaveral to Jupiter Inlet. Lack of quality data at some nearshore areas for this time period prevented complete bathymetric change comparison for the entire region, which is illustrated on the change plot (Figure 3-24). The area where change could not be evaluated exists on the inner shelf between Patrick AFB and Fort Pierce Inlet, most of which exists outside the sand resource areas. Only change calculations for Resource Areas B1 and B2 were affected by the lack of data, and in these cases, change rates for adjacent areas were considered analogous for borrow sites in Areas B1 and B2. Bathymetric change comparisons were available for most shoal areas being evaluated for sand resource extraction impacts.

Deposition was prominent along the inner shelf offshore Port Canaveral and Cocoa Beach, within the low relief area protected by Canaveral Shoals. Sediment transported south over Canaveral Shoals may be depositing material in this area as nearshore wave and current processes diminish south of Cape Canaveral. Depositional zones also were prominent in the shoal regions along the inner shelf from Fort Pierce south to Jupiter Inlet. An evaluation of shelf sediment sources from Cape Canaveral south to Palm Beach was completed under the ICONS study (Meisburger and Duane, 1971). Fine-grained sediments found on the shelf south of Canaveral Shoals is indicative of reduced sand transport to this area from the north. Because net littoral transport is from north to south, sediment supply from the south also is ruled out as a primary source. The ICONS study concluded that most shelf sediment is locally produced and only small quantities of sediment are being supplied to the shelf surface south of Canaveral Shoals from adjacent shelf areas or from the littoral drift system. Recent sediment samples collected offshore Fort Pierce Inlet indicated high quantities of carbonate and shell fragments (Figure 3-2), which is consistent with the sedimentary analysis completed under ICONS in 1971. It is likely that much of the deposition documented on the 1929/31 to 1929/73 change surface resulted from local growth of biogenic material.

3.2.4 Magnitude and Direction of Change

Patterns of seafloor erosion and accretion on the continental shelf seaward of the central east Florida coast documented the net direction of sediment transport throughout the study area (Figures 3-23 and 3-24). For the period 1877/83 to 1929/73, net sediment movement is from north to south. This direction of transport is consistent with historical shoreline change trends and channel dredging practice at entrances along the Florida coast (any sidecasting, nearshore, or offshore dumping is to the south of inlets). It also is consistent with the locations of FDEP designated zones of “critical erosion” at inlets (Figure 3-4). Although overall trends are helpful for understanding potential impacts of sand extraction from the OCS, the specific purpose of historical bathymetric change assessment is to quantify sediment erosion and accretion and to derive infilling rates specifically related to potential sand extraction sites.

Potential infilling rates at resource areas were evaluated by comparing deposition and erosion rates at and adjacent to proposed borrow sites. For all volume change calculations, the maximum of either erosion or deposition was used as an indicator of potential infilling, assuming that the larger of these two reflects the rate at which sediment would be available for transport (and infilling) at each site. To accurately assess the magnitude of change across the region, transport rates calculated for individual sites were normalized to the area of the largest borrow site polygon. As such, reasonable comparisons could be made between transport rates calculated throughout the study area.

For Sand Resource Area A1, volume change between 1956 and 1996 was used as an indicator of potential transport (infilling) rates (Figure 3-23). Seafloor erosion over the 40-yr period ranged from about 88,000 to 119,000 m^3/yr (Table 3-7). For Areas B1 and B2, potential infilling rates were calculated at areas located northeast and east of the borrow sites due to lack of data near the actual sites (Figure 3-24). Change between 1930 and 1967 for the site in Area B1 ranged from 38,000 to 64,000 m^3/yr, and change for the site in B2 ranged from 61,000 to 98,000 m^3/yr. Infilling rates at both borrow sites located within Area C1 ranged from 76,000 to 113,000 m^3/yr. Rates for Area D2 ranged from 72,000 to 104,000 m^3/yr. As expected, highest infilling rates are located seaward of Cape Canaveral. This reflects a more dynamic offshore environment near the Cape. Again, this calculation assumes that sediment eroded from areas nearby potential borrow sites reflects the rate at which material would be available for infilling the borrow sites. Further consideration should be given to local sources of shell material at southern sites when addressing infilling rates for specific projects in those areas. Rates of production of biogenic material are unknown, and their contribution to deposition in this area is undetermined. 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.

Table 3-7. Potential infilling rates at borrow sites.

Site	Normalized Infilling Rate (m^3/yr)
A1	88,000 to 119,000
B1	38,000 to 64,000
B2	61,000 to 98,000
C1 North	87,000 to 113,000
C1 South	77,000 to 112,000
D1	72,000 to 104,000

3.2.5 Net Longshore Sand Transport Rates

Shoreline and bathymetric change data documented net deposition north of inlets and net erosion along beaches south of inlets throughout the study area (see Figures 3-8 and 3-23). Bathymetric data coverage was not sufficient on a regional scale to quantify deposition and erosion patterns seaward of the high-water shoreline to closure depth. However, bathymetric change information is available for the area between Cape Canaveral and Port Canaveral Harbor. In combination with dredging records for Port Canaveral, net longshore transport was estimated at about 236,000 m^3/yr (308,000 cy/yr) just south of Cape Canaveral (Kraus et al., 1999). South of Port Canaveral entrance, net transport decreases to about 119,000 m^3/yr (155,000 cy/yr). According to Walton (1976) and Dean and O'Brien (1987), the net littoral transport rate remains relatively constant until Fort Pierce Inlet, at which point, net transport rates increase from approximately 140,000 to 184,000 m^3/yr (183,000 to 240,000 cy/yr) south to Jupiter Inlet.

3.3 SUMMARY

Shoreline position and nearshore bathymetric change documented four important trends relative to study objectives. First, the predominant direction of sediment transport on the continental shelf and along the outer coast between Cape Canaveral and Jupiter Inlet is north to south. The greatest amount of shoreline change in this study was associated with beaches adjacent to Cape Canaveral, Port Canaveral Entrance, and beaches south of St. Lucie Inlet.

Second, the most dynamic features within the study area, in terms of nearshore sediment transport are the beaches and shoals associated with Cape Canaveral. Areas of significant erosion and accretion are documented between 1956 and 1996 at Cape Canaveral, reflecting wave and current dynamics and the contribution of littoral sand transport from the north to shoal and spit migration. Depositional zones also are prominent in the shoal regions along the inner shelf from Fort Pierce south to Jupiter Inlet. Large quantities of carbonate and shell fragments observed in sediment samples collected from shoals in this region indicate that much of the deposition in this portion of the study area may have been locally produced.

Third, alternating bands of erosion and accretion documented between 1956 and 1996 at Cape Canaveral illustrate steady reworking of the upper shelf surface as sand ridges migrate from north to south. The process by which this is occurring at Area A1 suggests that the borrow site in this region would fill with sand transported from the adjacent seafloor at rates ranging from 88,000 to 119,000 m^3/yr. Areas of erosion and accretion documented between 1929/31 and 1929/73 between Port Canaveral Entrance and Jupiter Inlet indicate the amount of sediment available for infilling sites south of Port Canaveral Entrance is between 38,000 and 113,000 m^3/yr.

Finally, net longshore transport rates determined from seafloor changes in the littoral zone between Cape Canaveral and Port Canaveral entrance, in conjunction with dredging records for Port Canaveral entrance, indicate maximum transport rates near Cape Canaveral, with lower rates south of the entrance. Net longshore transport north of Port Canaveral entrance was estimated at about 236,000 m^3/yr. South of the Port, rates have been estimated to range from 119,000 m^3/yr immediately south of the entrance to 140,000 to 184,000 m^3/yr between Fort Pierce and Jupiter Inlets.

4.0 ASSESSMENT OF WAVE CLIMATE IMPACT BY OFFSHORE BORROW SITES

Excavation of an offshore borrow site can affect wave heights and the direction of wave propagation. The existence of an excavated hole or trench on the OCS can cause waves to refract toward the shallow edges of a borrow site. This alteration to a wave field by a borrow site may change local sediment transport rates, resulting in some areas experiencing a reduction in longshore transport and other areas showing an increase. To determine potential physical impacts associated with dredging borrow sites offshore the central east coast of Florida, 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 an evaluation of potential environmental impacts associated with alterations to nearshore wave patterns. To determine potential physical 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, has been applied to determine appropriate criteria for assessing impact significance.

To directly assess impacts to coastal processes associated with sand mining, an approach was utilized that considers spatial (longshore) and temporal aspects of the local wave climate, as described by Kelley et al. (2004). This method was applied by performing wave model runs using mean conditions developed from the entire 20-year WIS record, 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 1-year period (based on the 20 1-year wave records parsed from the full record). Applying this information, the average and standard deviation in calculated longshore sediment transport potential are 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 criterion would require that if any portion of the sediment transport potential curve associated with a sand mining project exceeds one-half the standard deviation of natural temporal variability in sediment transport potential, the site would be rejected. Conversely, a borrow site design would be accepted as long as the transport potential change determined for post-dredging conditions at a site occurs within the range of one-half the standard deviation.

The natural variability envelope provides a basis for judging the impacts of a borrow site relative to sediment transport processes along a coastline. Because there is a greater than 50% chance that the transport computed for a particular year will occur outside the $\pm 0.5\sigma$ envelope about the mean, impacts determined for a particular borrow site that occur within this range will be indistinguishable from observed natural variations.

An example of this method taken from previous work (Byrnes et al., 2003) is shown in Figure 4-1, where alterations in wave climate caused by dredging a series of borrow sites offshore northeastern North Carolina were determined to be insignificant relative to natural variability. For the modeled shoreline, the area where computed change in transport potential comes closest to exceeding the significance envelope was at a shoreline point near N 3,967,000 UTM. At this location, transport potential change was determined to be approximately 30,000 m^3/yr, which was less than the approximate 40,000 m^3/yr allowable limit of change set by the significance criterion. Due to the relatively high natural variability in wave climate in this area, simulated shoreline change induced by offshore borrow site dredging could not be identified relative to natural changes. For this reason, sites with large natural variation in wave climate and associated sediment transport potential may have larger simulated impacts associated with an offshore sand mining project.

As a management tool for the MMS, this methodology provides several advantages over methods previously employed 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 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, 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 determining impact significance.

4. Similar to methodologies incorporated in previous MMS studies, the longshore spatial distribution of borrow site impacts was considered. However, an acceptable limit of longshore sediment transport variability was computed from the temporal component of the analysis. Therefore, the final results of this analysis provided a spatially-varying envelope of natural variability 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.

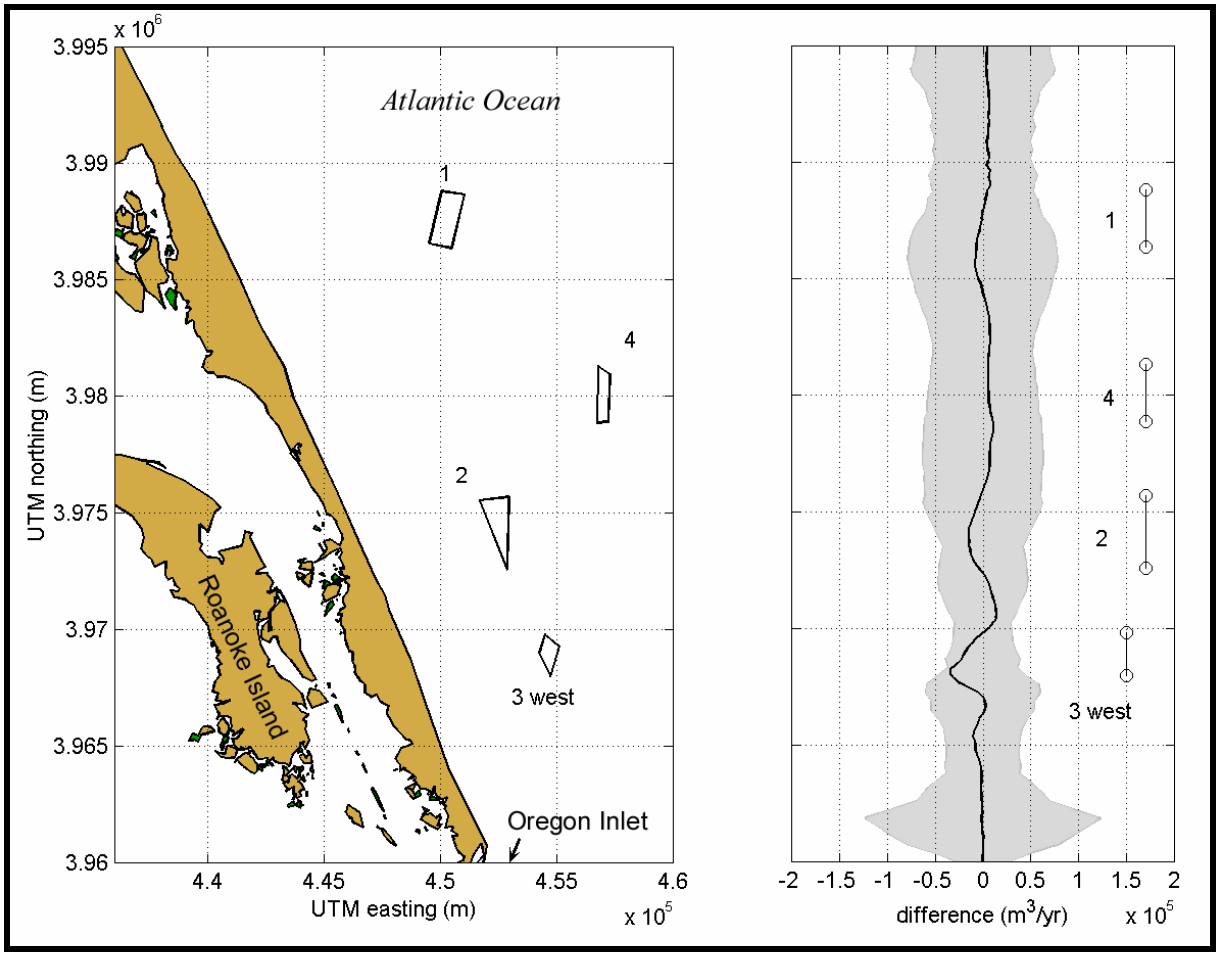

Figure 4-1. Natural variability in sediment transport potential for determining significance of borrow site dredging impacts (Byrnes et al., 2003). The difference plot illustrates modeled change in net transport potential (solid black line) resulting from dredging four borrow sites offshore North Carolina. The plot also shows the dredging significance criterion envelope ($\pm\sigma$) determined for this shoreline (gray-shaded envelope).

4.1 ANALYSIS APPROACH

Sediment transport rates along a coastline are dependent on local wave climate. For this study, nearshore wave heights and directions along the shoreline landward of proposed borrow sites were estimated using the USACE spectral wave model STWAVE, which was used to simulate the propagation of offshore waves to the shoreline. Offshore wave data available from 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 versus energy) spectra were used as input to the model. STWAVE is able to simulate wave refraction and shoaling induced by changes in bathymetry and by wave interactions with currents. The model includes a wave breaking model based on water depth and wave steepness. Model output includes significant wave height (H_s), peak wave period (T_p), and mean wave direction ($\bar{\theta}$).

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. As such, STWAVE can propagate waves only in directions within the ±87.5° half plane. A benefit of using this single pass approach is that it uses minimal computer memory because the only memory-resident spectral data are for two grid columns. Accordingly, changing wave spectra across each grid column are computed using information solely from the previous grid column.

STWAVE is based on a form of the wave action balance equation. The wave action density spectrum, which includes the effects of currents, is conserved along wave rays. In the absence of currents, wave rays correspond to wave orthogonals, and the action density spectrum is equivalent to the wave energy density spectrum. A diagram showing the relationship 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., white capping, breaking, wind input),
α = wave orthogonal direction,
μ = wave ray direction (direction of energy propagation),
ω_r = relative angular frequency ($2\pi f_r$),
C_a, C_{ga} = absolute wave celerity and group celerity, respectively.

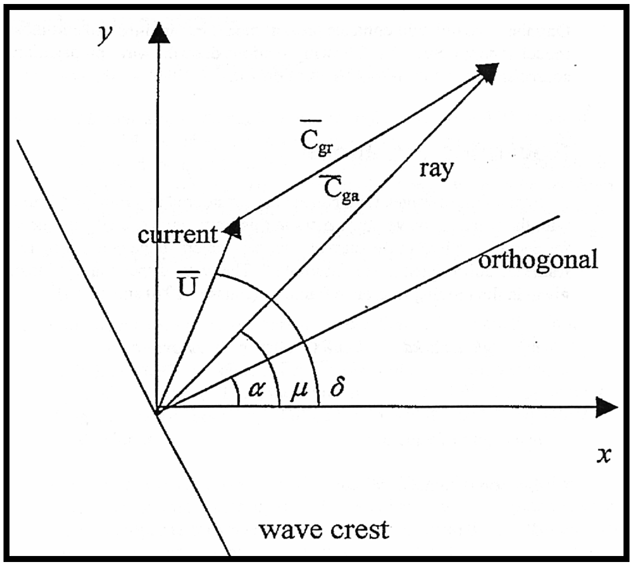

Figure 4-2. Wave and current vectors used in STWAVE. Subscript *a* denotes values in the *absolute* frame of reference, and subscript *r* denotes values in the *relative* frame of reference (with currents).

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

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

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 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

Offshore wave conditions used as input for wave modeling can be derived from two main sources: measured spectral wave data from offshore data buoys or hindcast simulation time series data (Hubertz et al., 1993). In general, buoy data are the preferred source of wave information for modeling because they represent actual offshore measurements rather than hindcast information derived from large-scale models. However, very few sites along the U.S. east coast have wave measurement records of sufficient length to justify their use as a source of long-term information. Offshore central east Florida, sources of measured directional wave data include the Florida Coastal Data Network (CDN) (Wang et al., 1990) and various short-term deployments of individual gages (e.g., the 1991 University of Florida deployment of a PUV gage offshore Jupiter Island [Harris, 1991]). Past comparisons of WIS hindcast data and waves measured offshore eastern Florida illustrated general agreement (Ramsey et al., 1995), suggesting that WIS hindcast data sets are a valid source of wave data for this study.

Wave input conditions for simulations offshore central east Florida were developed using hindcast data from WIS Stations AU2019 (19) for Area A, AU2016 (16) for Area B, AU2014 (14) for Area C, and AU2013 (13) for Area D. Locations of these WIS stations are shown with the limits of computational grids in Figure 4-3. WIS records cover a 20-year period from January 1976 to December 1995. Station 19 is located approximately 29 km east-northeast of Cape Canaveral in 35 m water depth. Station 16 is located in 45 m water depth approximately 45 km east of Sebastian Inlet. Station 14 is located in 55 m water depth approximately 18 km east of St. Lucie Inlet, and Station 13 is located approximately 10 km east of Jupiter Inlet in 45 m water depth.

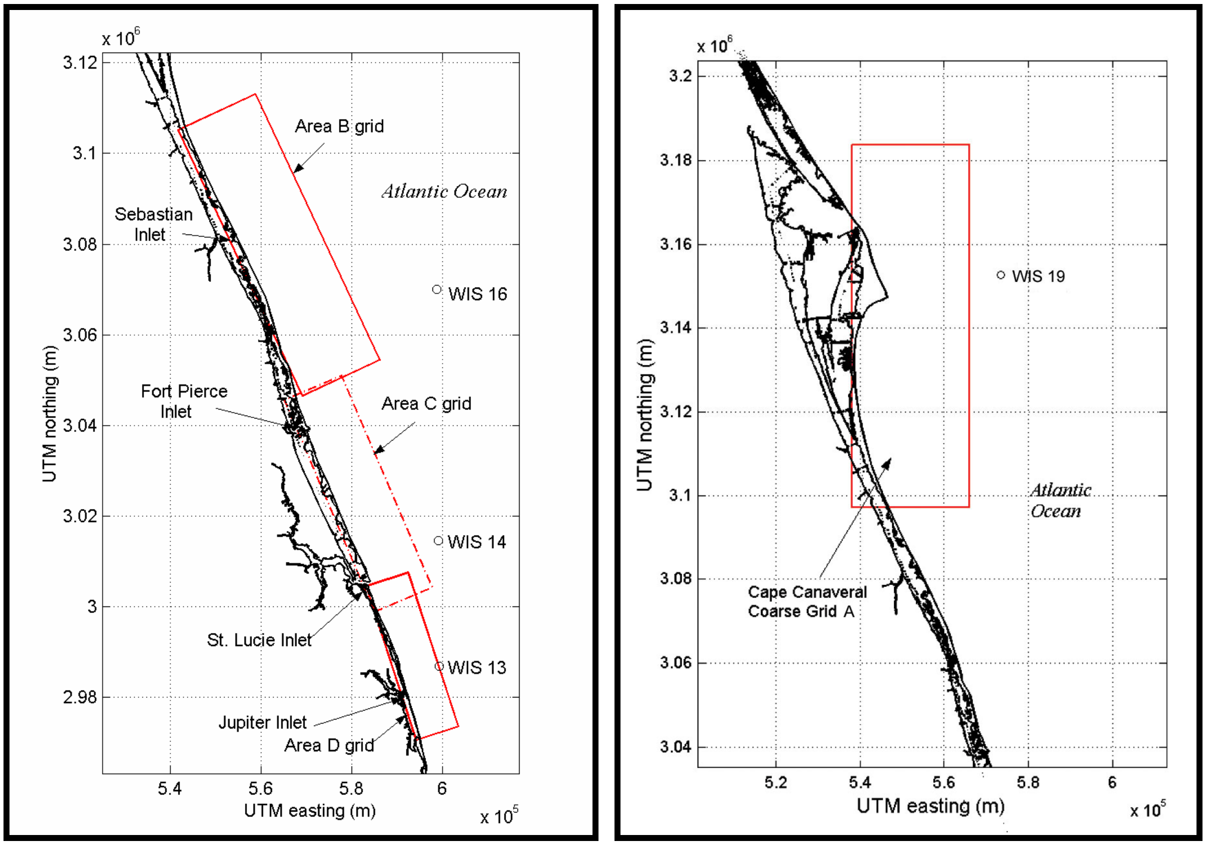

Figure 4-3. Shoreline of central east Florida with coarse grid limits and WIS stations used to evaluate potential dredging impacts from offshore sand mining.

Two wave roses showing percent occurrence of different wave conditions for each of the four WIS stations are shown in Figures 4-4 through 4-7. The first rose for Station 19 illustrates variations in wave height distribution by direction (Figure 4-4). Most waves (90%) in the record occur within the 30° and 120° compass sector, and the greatest percentage of waves (43%) is from the east-northeast. Mean height for all waves in the record is 1.3 m, and the standard deviation is 0.7 m. Mean height for waves along the dominant wave direction is 1.4 m, with a standard deviation of 0.7 m. The second rose in Figure 4-4 illustrates the distribution of peak wave period in the record. Mean peak period for the entire record is 9.3 sec, and 38% of simulated waves have peak periods greater than 9 sec.

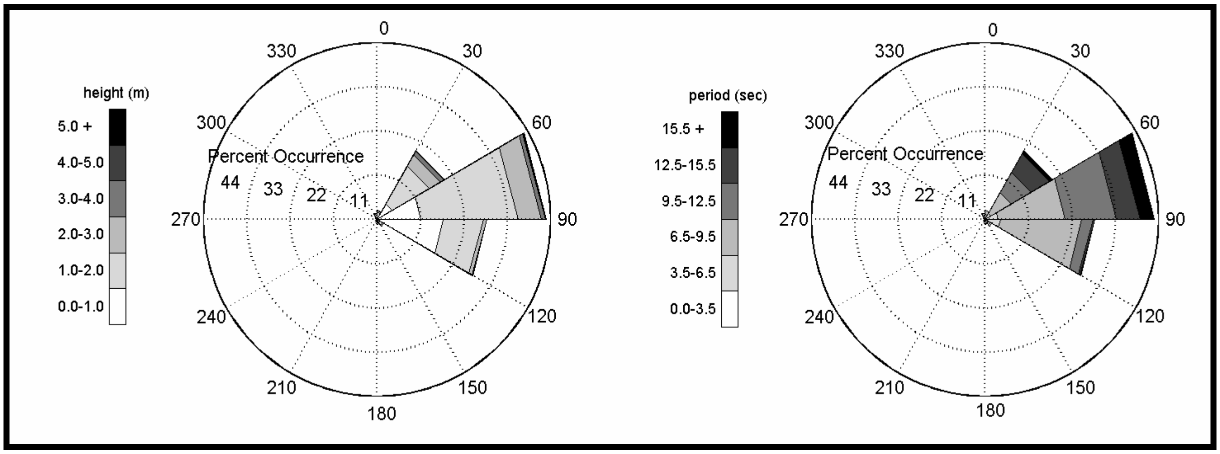

Figure 4-4. Wave height and period for hindcast data from WIS station AU2019, January 1976 and December 1995. Direction indicates from where waves were traveling, relative to true north. Radial length of gray tone segments indicates percent occurrence for each range of wave height and period.

Wave plots for Station 16 are illustrated in Figure 4-5. Most waves (89%) in the WIS record occur within the compass sector between 30° and 120°. Dominant wave direction is between 60° and 90°, from which 45% of waves in the record propagate. Mean height for all waves in the record is 1.3 m, and the standard deviation is 0.7 m. Mean height for waves from the dominant wave direction is 1.4 m, and the standard deviation is 0.7 m. The second rose in Figure 4-5 shows the distribution of peak wave period in the record. A significant number of wave events (38%) have peak periods greater than 9 sec, and the mean peak period for the entire record is 9.3 sec.

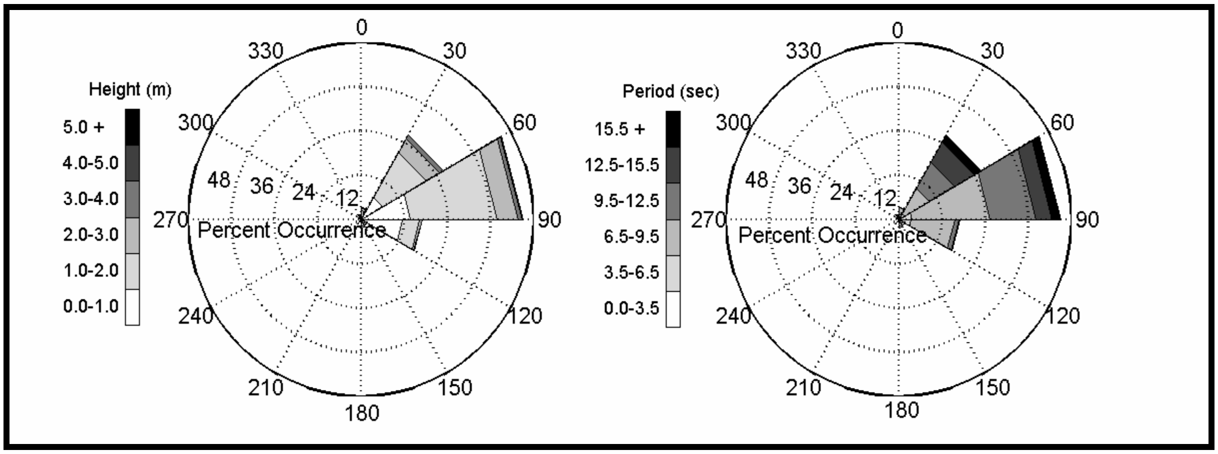

Figure 4-5. Wave height and period for hindcast data from WIS Station AU2016, January 1976 and December 1995. Direction indicates from where waves were traveling relative to true north. Radial length of gray tone segments indicates percent occurrence of each range of wave height and period.

Wave plots for Station 14 are shown in Figure 4-6. Most waves (76%) occur within the 30° and 90° compass sector. Dominant wave direction is between 30° and 60°, from which 39% of waves in the record propagate. Mean height for all waves is 1.2 m, with a standard deviation of 0.7 m. Mean height for waves from the dominant direction is 1.3 m, and the standard deviation is 0.7 m. A significant number of wave events (40%) have peak periods greater than 9 sec, and the mean peak period for the entire record is 9.1 sec.

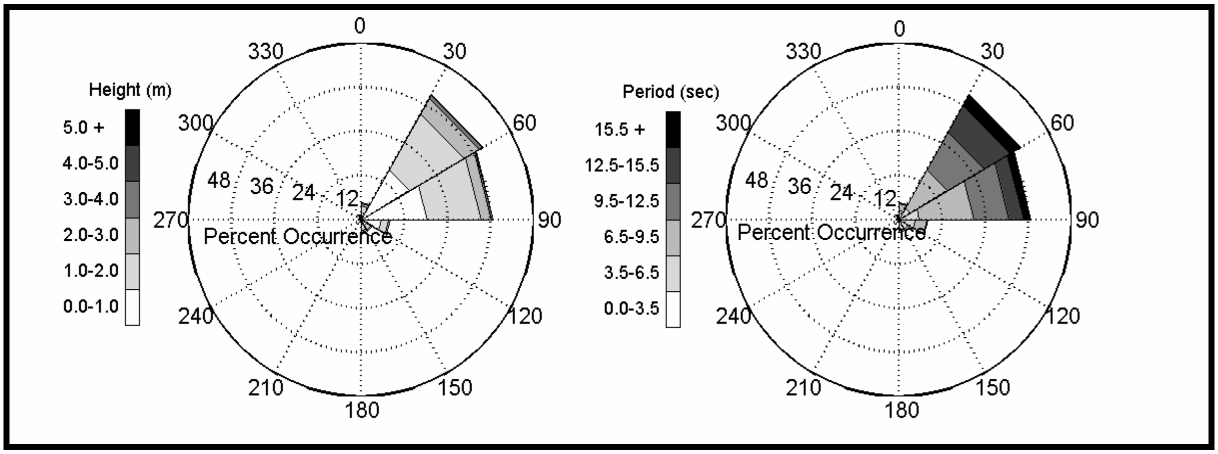

Figure 4-6. Wave height and period for hindcast data from WIS Station AU2014, January 1976 and December 1995. Direction indicates from where waves were traveling relative to true north. Radial length of gray tone segments indicates percent occurrence of each range of wave height and period.

Plots for Station 13, offshore Jupiter Inlet, illustrate that most waves (73%) propagate onshore from between 30° and 90° (Figure 4-7). Similar to Station 14, dominant wave direction is between 30° and 60°, from which 44% of waves in the record propagate. Mean height for all waves in the record is 1.1 m, and the standard deviation is 0.7 m. Mean wave height from the dominant wave direction is 1.1 m, and the standard deviation is 0.7 m. For wave period, a significant number of wave events (38%) have peak periods greater than 9 sec, and the mean peak period for the entire record is 8.8 sec.

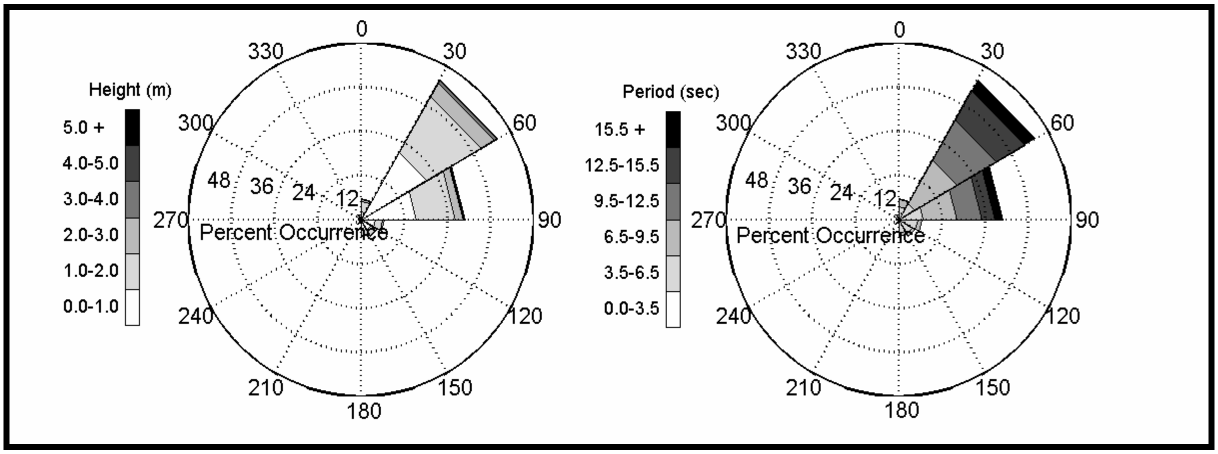

Figure 4-7. Wave height and period for hindcast data from WIS Station AU2013, January 1976 and December 1995. Direction indicates from where waves were traveling relative to true north. Radial length of gray tone segments indicates percent occurrence of each range of wave height and period.

WIS station plots illustrate that the dominant direction of wave propagation shifts northward from Station 19 to Station 13. This results from the combined influence of the Florida Current and the sheltering effect of Bahama Bank, 100 km east of Jupiter Inlet. There also is a general trend of slightly smaller wave heights and shorter wave periods for the southernmost WIS Station (13) compared with Station 19.

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

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

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

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

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 principle direction of wave travel, and G_o is a constant dependent on θ and s. The spreading parameter s is evaluated using the expression

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

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 that is based on parameters from the WIS record, and that distributes spectral energy based on wave peak frequency and wind speed. An example of a two-dimensional spectrum generated by this method is presented in Figure 4-8.

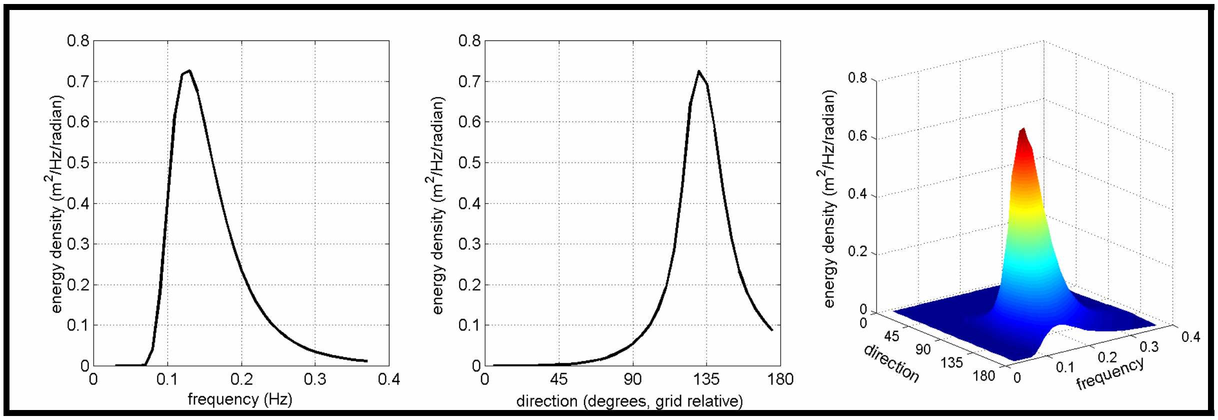

Figure 4-8. STWAVE input spectrum developed using WIS 20-year hindcast data with Goda (1985) method of computing frequency and direction spectrum. Plots show a) frequency distribution of energy at peak direction, b) directional distribution of energy at peak frequency, and c) surface plot of two-dimensional energy spectrum (H_{mo} = 0.9 m, θ_{mean} = 130° grid relative).

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

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

4.1.1.2 Grid Development

Input spectra and two coarse grids were developed for each sand resource area for simulating wave propagation over existing and post-dredging bathymetry. A fine grid, nested within coarse grids, was developed for each area to obtain greater resolution of wave characteristics in the nearshore, landward of borrow sites. Most recent surveys (see Section 3.0) were the primary source of bathymetric data for creating grids. However, these data were supplemented by more recent local bathymetric data where available. Contour plots of existing conditions grids for each modeled area are shown in Figures 4-9 (Area A), 4-10 (Area B), 4-11 (Area C), and 4-12 (Area D).

Table 4-1. Input wave spectra parameters used for existing and post-dredging STWAVE runs for modeled Area A.

	STWAVE Model Input Condition	Percent Occurrence	H_{mo} Wave Height (m)	Peak Wave Period, T_p (sec)	Peak Wave Direction, θ_p (° true north)	Peak Wave Direction, θ_p (grid relative)	Direction Bin (grid relative)
Period Band 1	1A	8.2	1.7	7.7	55	55	30-60
	2A	20.8	1.4	7.7	80	80	60-90
	3A	24.6	1.0	7.7	100	100	90-120
	4A	2.3	1.5	6.3	130	130	120-150
Period Band 2	5A	6.5	1.7	12.5	60	60	30-60
	6A	28.5	1.6	14.3	65	65	60-90
	7A	3.4	1.5	11.1	100	100	90-120

Table 4-2. Input wave spectra parameters used for existing and post-dredging STWAVE runs for modeled Area B.

	STWAVE Model Input Condition	Percent Occurrence	H_{mo} Wave Height (m)	Peak Wave Period, T_p (sec)	Peak Wave Direction, θ_p (° true north)	Peak Wave Direction, θ_p (grid relative)	Direction Bin (grid relative)
Period Band 1	1B	2.3	1.9	6.9	25	50	33.75-56.25
	2B	6.5	1.8	7.6	45	70	56.25-78.75
	3B	7.0	1.6	7.7	60	85	78.75-90.00
	4B	7.2	1.5	7.7	70	95	90.00-101.25
	5B	24.7	1.1	7.7	90	115	101.25-123.75
	6B	5.7	1.1	6.9	105	130	123.75-146.25
Period Band 2	7B	6.7	1.7	11.4	50	75	56.25-78.75
	8B	15.7	1.7	13.9	60	85	78.75-90.00
	9B	8.4	1.7	12.4	70	95	90.00-101.25
	10B	6.6	1.7	10.8	90	115	101.25-123.75

Dimensional characteristics of each grid are presented in Table 4-5. Geographical limits for each grid were chosen based on wave conditions selected for model simulations. Wave conditions with relatively small angles to the shoreline require a wide grid so the area of potential impact does not occur within the shadow of the lateral grid boundaries. Depths at the offshore boundary of the coarse grid for Area A ranged from 19 to 30 m (relative to the National Geodetic Vertical Datum [NGVD]), and the grid extends about 87 km alongshore. The coarse grid for Area B covers a region that extends approximately 17 km offshore and 65 km alongshore. Depths at the offshore boundary vary between 11 and 24 m (NGVD), with a mean depth of approximately 20 m. The coarse grid developed for Area C extends approximately 12 km offshore and 51 km alongshore. Depths at the offshore boundary vary between 14 and 44 m (NGVD), with a mean depth of approximately 21 m. Finally, the coarse grid developed for Area D extends approximately 9 km offshore and 36 km alongshore. Depths at the offshore boundary vary between 18 and 138 m (NGVD), with a mean depth of approximately 47 m.

Table 4-3. Input wave spectra parameters used for existing and post-dredging STWAVE runs for modeled Area C.

	STWAVE Model Input Condition	Percent Occurrence	H_{mo} Wave Height (m)	Peak Wave Period, T_p (sec)	Peak Wave Direction, θ_p (° true north)	Peak Wave Direction, θ_p (grid relative)	Direction Bin (grid relative)
Period Band 1	1C	4.5	1.6	6.8	32	55	33.75-56.25
	2C	12.3	1.5	7.5	47	70	56.25-78.75
	3C	7.2	1.4	7.5	72	95	78.75-90.00
	4C	8.4	1.2	7.4	67	90	90.00-101.25
	5C	11.5	1.0	6.9	87	110	101.25-123.75
	6C	4.5	1.1	5.4	107	130	123.75-146.25
Period Band 2	7C	18.4	1.4	12.3	52	75	56.25-78.75
	8C	11.9	1.5	14.0	62	85	78.75-90.00
	9C	7.5	1.4	12.1	67	90	90.00-101.25
	10C	2.0	1.1	11.1	87	110	101.25-123.75

Table 4-4. Input wave spectra parameters used for existing and post-dredging STWAVE runs for modeled Area D.

	STWAVE Model Input Condition	Percent Occurrence	H_{mo} Wave Height (m)	Peak Wave Period, T_p (sec)	Peak Wave Direction, θ_p (° true north)	Peak Wave Direction, θ_p (grid relative)	Direction Bin (grid relative)
Period Band 1	1D	7.0	1.4	6.9	32	50	33.75-56.25
	2D	15.3	1.3	7.4	47	65	56.25-78.75
	3D	10.8	1.2	7.3	67	85	78.75-90.00
	4D	3.3	1.3	5.8	77	95	90.00-101.25
	5D	5.9	1.2	5.5	92	110	101.25-123.75
	6D	4.1	1.1	4.9	117	135	123.75-146.25
PB 2	7D	24.5	1.3	12.9	57	75	56.25-78.75
	9D	12.6	1.3	13.0	62	80	78.75-90.00

Post-dredging coarse grids were developed by imposing modifications to the existing conditions bathymetry; Table 4-6 presents the resource characteristics of modeled borrow sites. For each site, bathymetry was excavated to the indicated depth. Bathymetry deeper than the excavated depth was not modified. For each modeled area, the same fine grid was used for existing conditions and post-dredging simulations. Spatially varying boundary conditions (wave spectra) for fine grids were extracted from coarse grid simulations. As such, the fine grid solution was nested within the coarse grid solution.

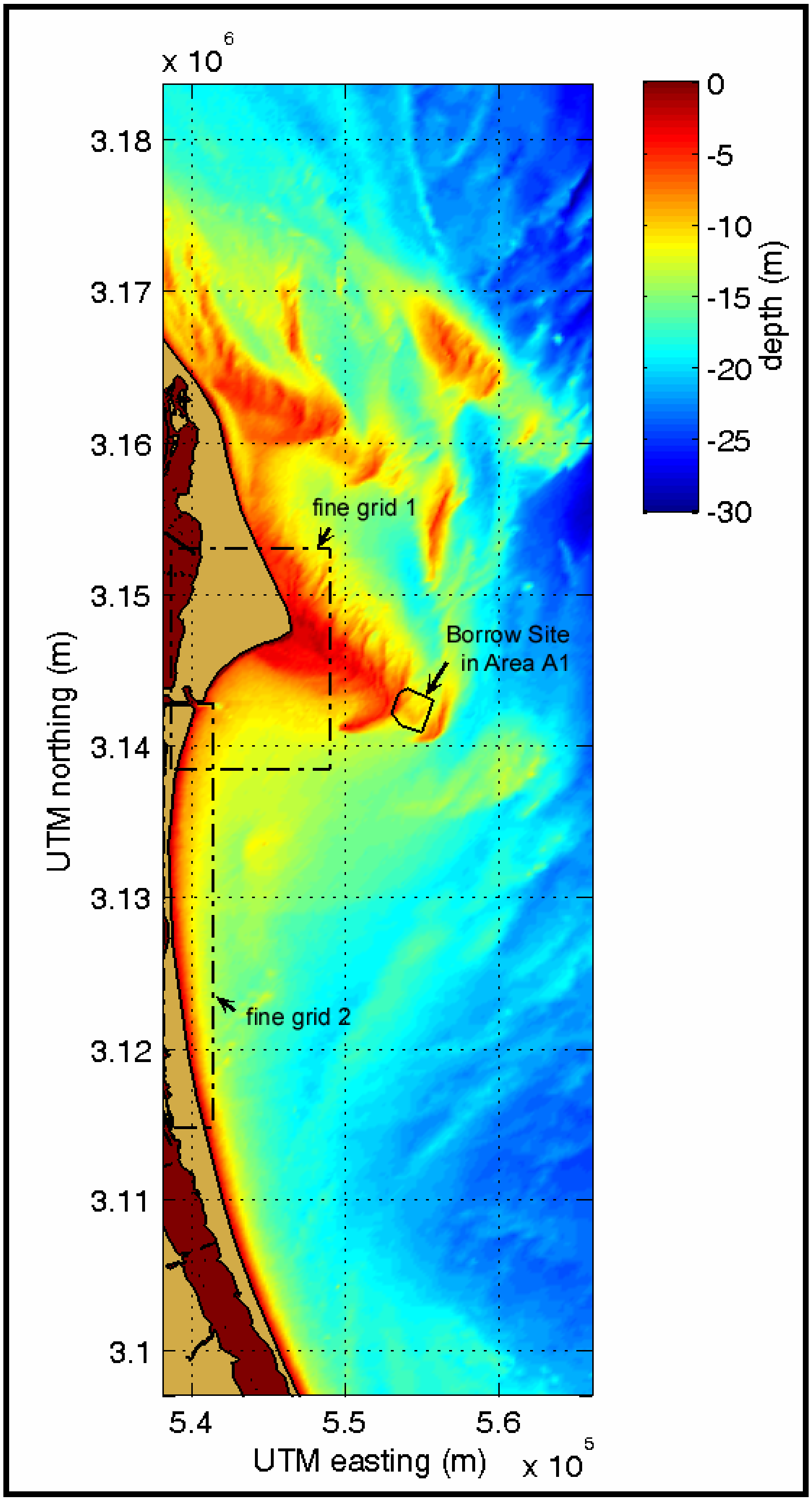

Figure 4-9. Coarse model grid (200 x 200 m spacing) used for STWAVE simulations offshore Cape Canaveral, FL. Depths are relative to NGVD. Borrow site location is indicated by the solid black line, and fine grid limits are indicated by a dashed line.

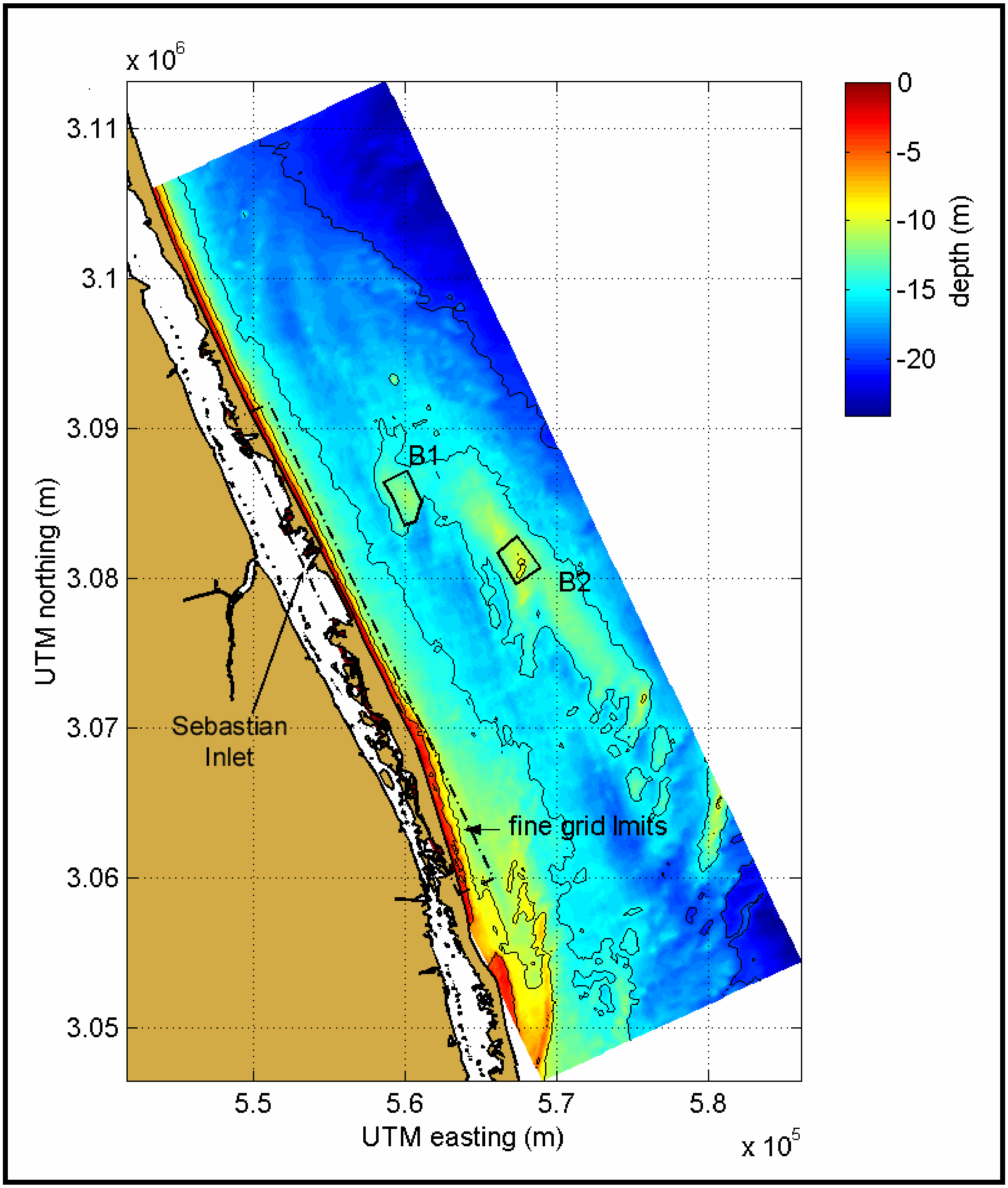

Figure 4-10. Coarse model grid (200 x 200 m spacing) used for STWAVE simulations offshore Sebastian Inlet, FL. Depths are relative to NGVD. Borrow site locations are indicated by solid black lines, and fine grid limits are indicated by a dashed line. B1 is the borrow site in Sand Resource Area B1, and B2 is the borrow site in Sand Resource Area B2.

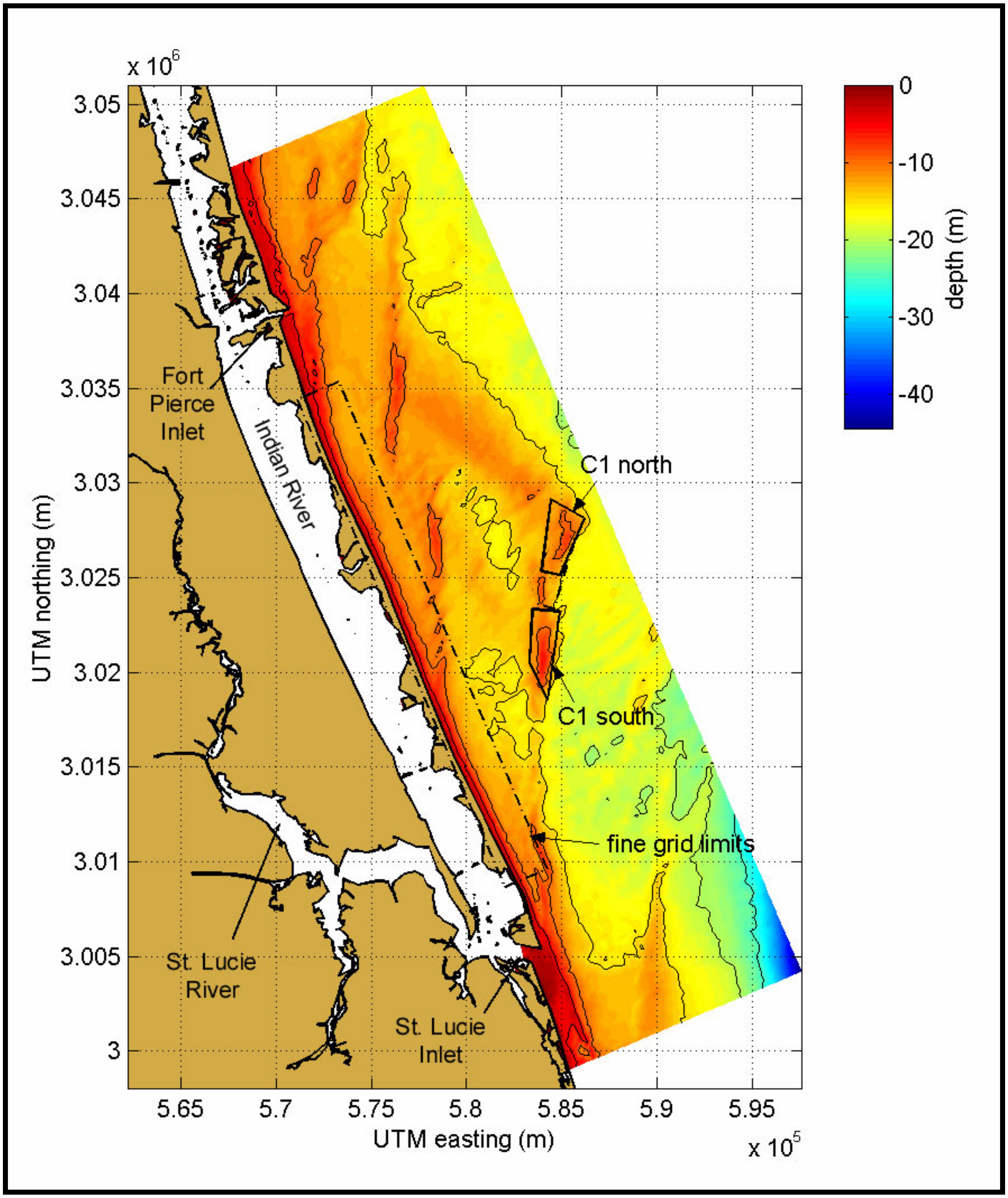

Figure 4-11. Coarse model grid (200 x 200 m spacing) used for STWAVE simulations offshore St. Lucie Inlet, FL. Depths are relative to NGVD. Borrow site locations are indicated by solid black lines, and fine grid limits are indicated by a dashed line. C1 north is the northern borrow site in Sand Resource Area C1, and C1 south is the southern borrow site in Sand Resource Area C1.

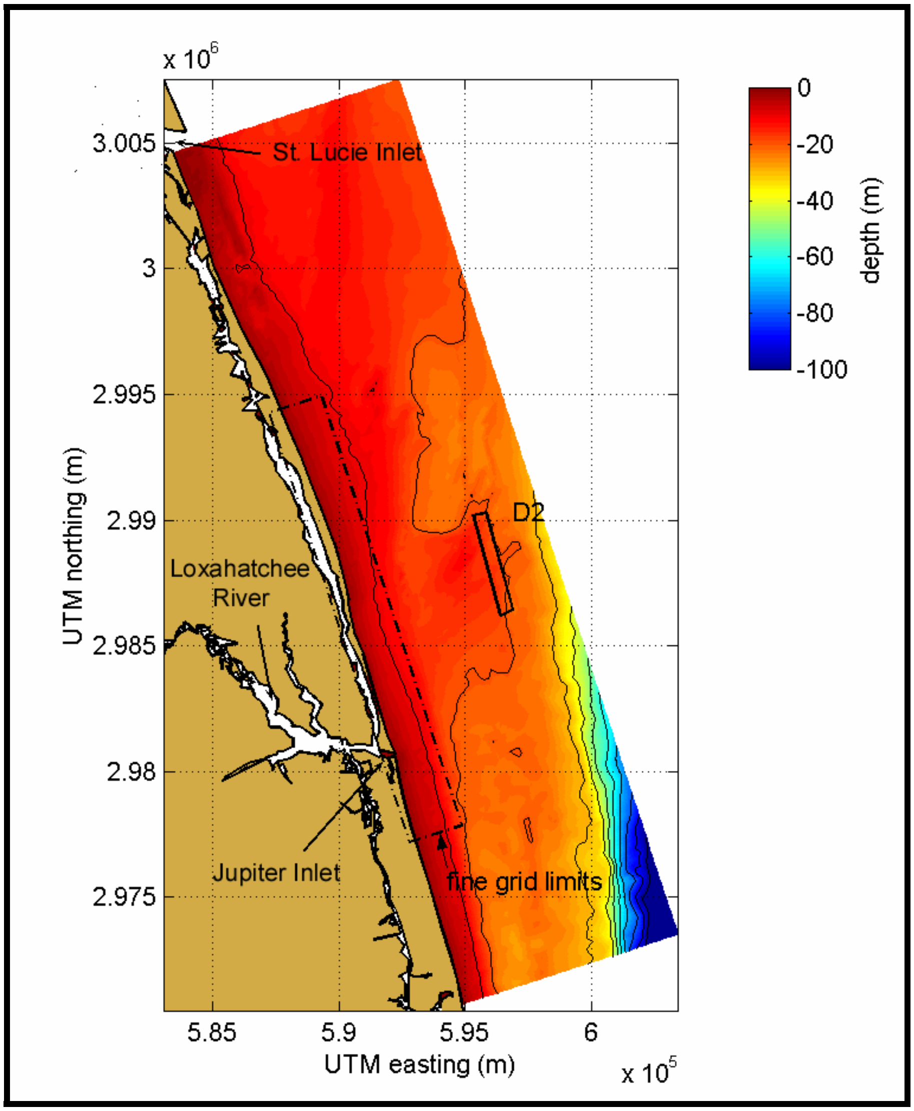

Figure 4-12. Coarse model grid (200 x 200 m spacing) used for STWAVE simulations offshore Jupiter Inlet, FL. Depths are relative to NGVD. Borrow site locations are indicated by solid black lines, and fine grid limits are indicated by a dashed line. D2 is the borrow site that extends from Sand Resource Area D1 into Sand Resource Area D2 along the Federal-State boundary.

Table 4-5. Numerical grid dimensions for offshore (coarse) and nearshore (fine) grids. Dimensions are given as cross-shore x alongshore.

Region	Coarse Grid (200 m spacing)		Fine Grid (20 m spacing)		Grid Angle (° true north)
	Nodes	Distance (km)	Nodes	Distance (km)	
Area A	141 x 434	28 x 87	520 x 730	10 x 15	0
			160 x 1400	3 x 28	
Area B	95 x 325	19 x 65	13 1 x 1751	2.6 x 35	-25
Area C	70 x 255	14 x 51	121 x 1401	2.4 x 28	-23
Area D	50 x 180	10 x 36	111 x 901	2.2 x 18	-18

Table 4-6. Sand resource characteristics at potential borrow sites in resource areas offshore central east Florida.

Resource Area	Borrow Site Surface Area (x 10^6 m^2)	Maximum Excavation Depth (m)	Borrow Site Sand Volume (x 10^6 m^3)	D10 (mm)	D50 (mm)	D90 (mm)
A1	5.39	12	13.6	0.70	0.32	0.21
B1	4.62	15	11.0	1.15	0.60	0.28
B2	3.48	13	7.6	1.49	0.47	0.25
C1 north	5.16	12	5.8	1.96	0.61	0.26
C1 south	4.71	12	8.8	0.62	0.29	0.18
D2	2.25	20	4.1	0.59	0.31	0.20

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.

4.1.2 Sediment Transport Potential

As a first step in evaluating sediment transport along the coastline of central east Florida, calculations of sediment transport potential were performed to indicate the maximum quantity of sand transport possible based on a sediment-rich environment. Results from the spectral wave modeling formed the basis for quantifying changes in sediment transport rates along the beach because wave-induced transport is a function of wave breaker 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 longshore analyses is based on work of the Rosati et al. (2002). 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 a 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 activities. Computations of sediment transport rates for each wave condition was performed and then weighted by the annual percentage occurrence. Sediment transport potential was computed for existing and post-dredging conditions with the equations described in Appendix B.

4.2 MODEL RESULTS

Redistribution of wave energy and alteration of wave directions resulting from offshore sand excavation are expected to change longshore sediment transport patterns landward of potential sand borrow sites in central east Florida. Depending on the net direction of local sediment transport, the influence of borrow site conditions can either increase or decrease net littoral drift. Example model cases for each potential sand borrow site offshore central east Florida are discussed in the following subsections. Complete results for the four modeled regions, showing wave heights and wave height difference plots between existing and post-dredging conditions for all modeled wave cases, is provided in Appendix C.

4.2.1 Wave Modeling

From existing conditions model results, bottom features offshore central east Florida modified the wave field as it propagated shoreward. As an example, the shoal in the vicinity of Borrow Sites C1 north and C1 south (approximately 7 m water depth) refracts and focuses wave energy, resulting in an area of increased wave heights shoreward of the shoal (Figure 4-13). Wave heights landward of the shoal were about 0.3 m greater than wave heights seaward of the shoal. As the shoal focused wave energy and caused an increase in wave height in one area, there was a corresponding decrease in wave energy in adjacent areas. Because energy was conserved, wave focusing behind the shoal caused a reduction of energy at the southern edge of the shoal, which is illustrated by reduced wave heights.

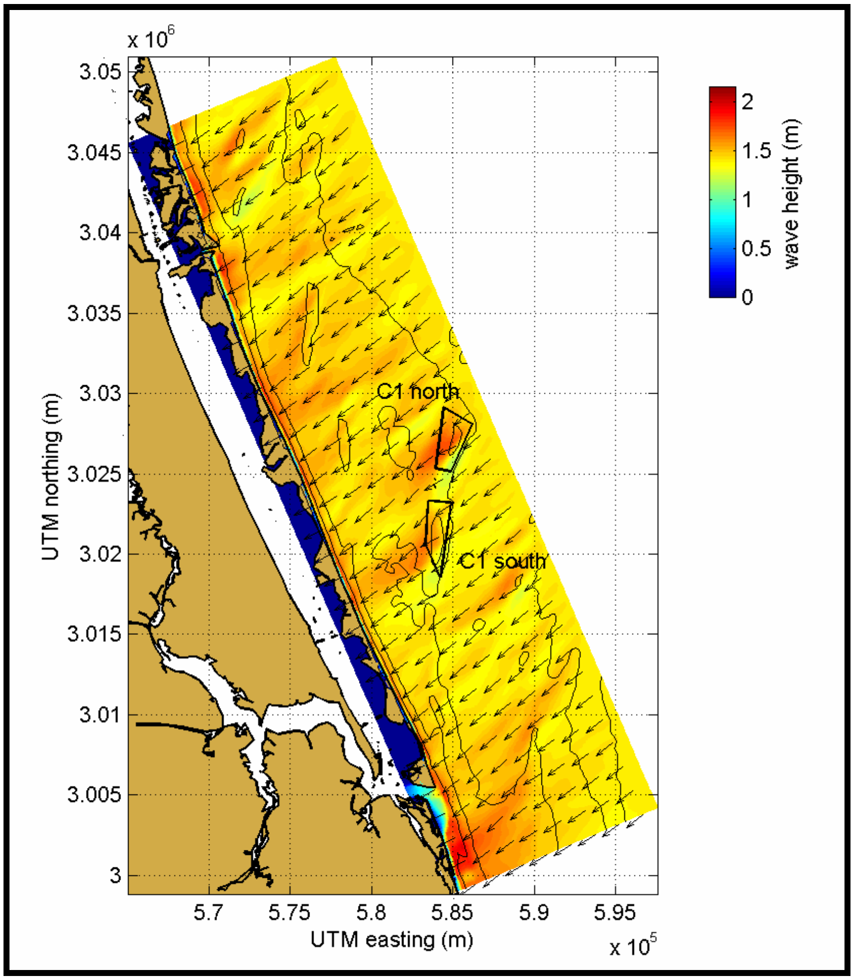

Figure 4-13. STWAVE output for the coarse grid in wave modeling Area C (200 x 200 m grid cells) offshore St. Lucie Inlet (H_{mo} = 1.4 m, T_p = 12.3 sec). Color contours indicate H_{mo} wave height. Vectors indicate mean wave direction. Seafloor contours are shown at 5 m intervals.

In addition to the effects of bottom features far offshore, waves were refracted by straight and parallel bottom contours in the nearshore. In Figure 4-14, fine grid model results illustrate how wave directions changed as the wave field propagates shoreward. For the same northeast wave condition as in Figure 4-13, waves refracted and the mean direction of wave propagation near the shoreline became shore-normal (perpendicular to the shoreline). In addition to the change in wave direction, wave heights also were modified by nearshore bathymetry. Waves began to shoal (increase in height) about 400 m offshore and increased in height by 0.2 m before breaking began. Wave heights were reduced as energy was dissipated in the surf zone, which was about 120 m wide in this example.

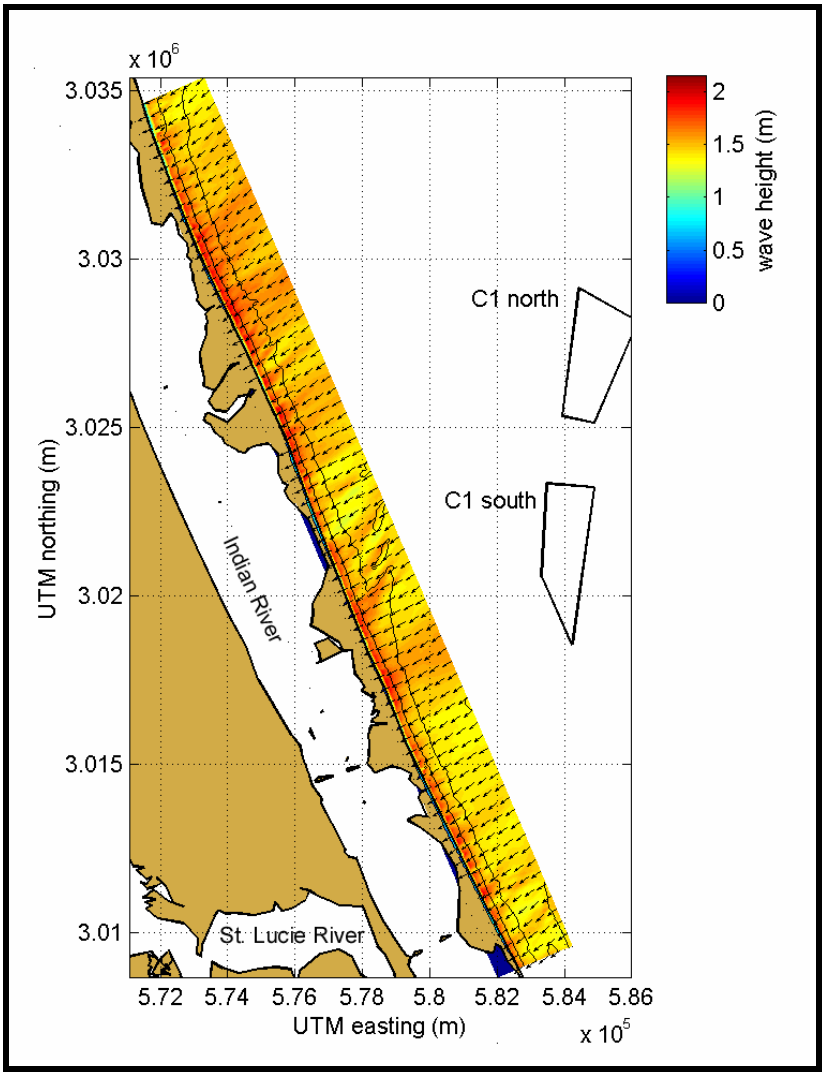

Figure 4-14. STWAVE output for the fine grid in wave modeling Area C (20 x 20 m grid cells) offshore St. Lucie Inlet (H_{mo} = 1.4 m, T_p = 12.3 sec). Color contours indicate H_{mo} wave height. Vectors indicate mean wave direction. Seafloor contours are shown at 5 m intervals.

Overall, post-dredging wave model output illustrated reduced wave heights landward of borrow sites and increased wave heights at the longshore limits of each borrow site. As waves propagated across a borrow site (deeper water than the surrounding area), wave refracted away from the center of the borrow site and toward the shallower edges. The net effect was 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 a borrow site.

This shadowing effect was apparent in the wave height difference plot presented in Figure 4-15. Color contours represent wave height differences between model results computed for existing and post-dredging conditions. For this particular wave case, there was an obvious interaction between the two borrow sites, as Site C1 south fell within the influence of Site C1 north (i.e., C1 south is in the shadow zone of C1 north). Not all wave cases for this modeled area exhibited this same overlapping influence. Maximum wave height reduction occurred landward of Site C1 south, where wave heights were reduced by 0.2 m. The areas of greatest wave height increase were found along the southeastern edges of both sites, where wave heights increased 0.9 m over existing conditions.

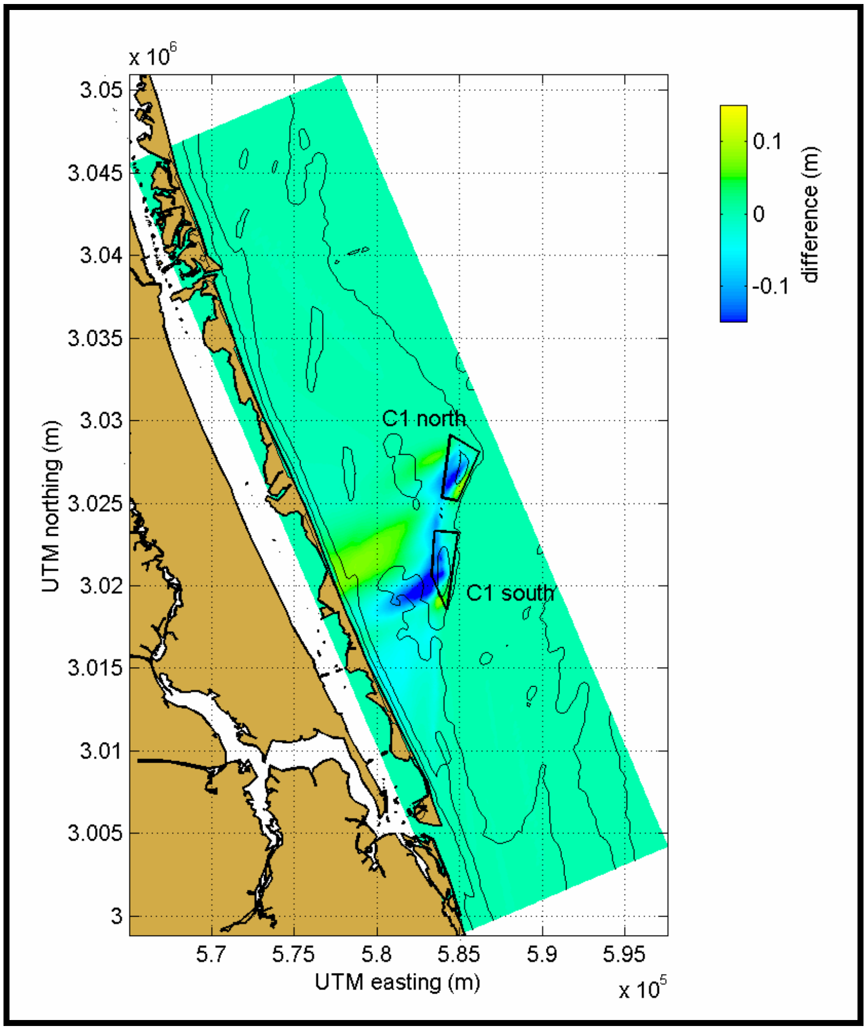

Figure 4-15. Wave height difference plot ($H_{difference} = H_{post} - H_{existing}$) for coarse grid model for St. Lucie Inlet. Seafloor contours are shown at 5 m intervals.

Because these are spectral wave model results, and because different frequencies in the spectrum are refracted by varying degrees at the borrow sites, areas of increased and reduced wave height gradually diffuse as the wave field approaches shore. This resulted in smaller changes in wave heights close to the shoreline (Figure 4-16). Another result of the energy diffusion process was that the length of shoreline affected by a borrow site (or combination of borrow sites) can be considerably longer than the borrow site. In Figure 4-16, the length of affected shoreline was approximately three times longer than the alongshore limits of the two borrow sites (i.e., the north corner of Site C1 north and the south corner of Site C1 south).

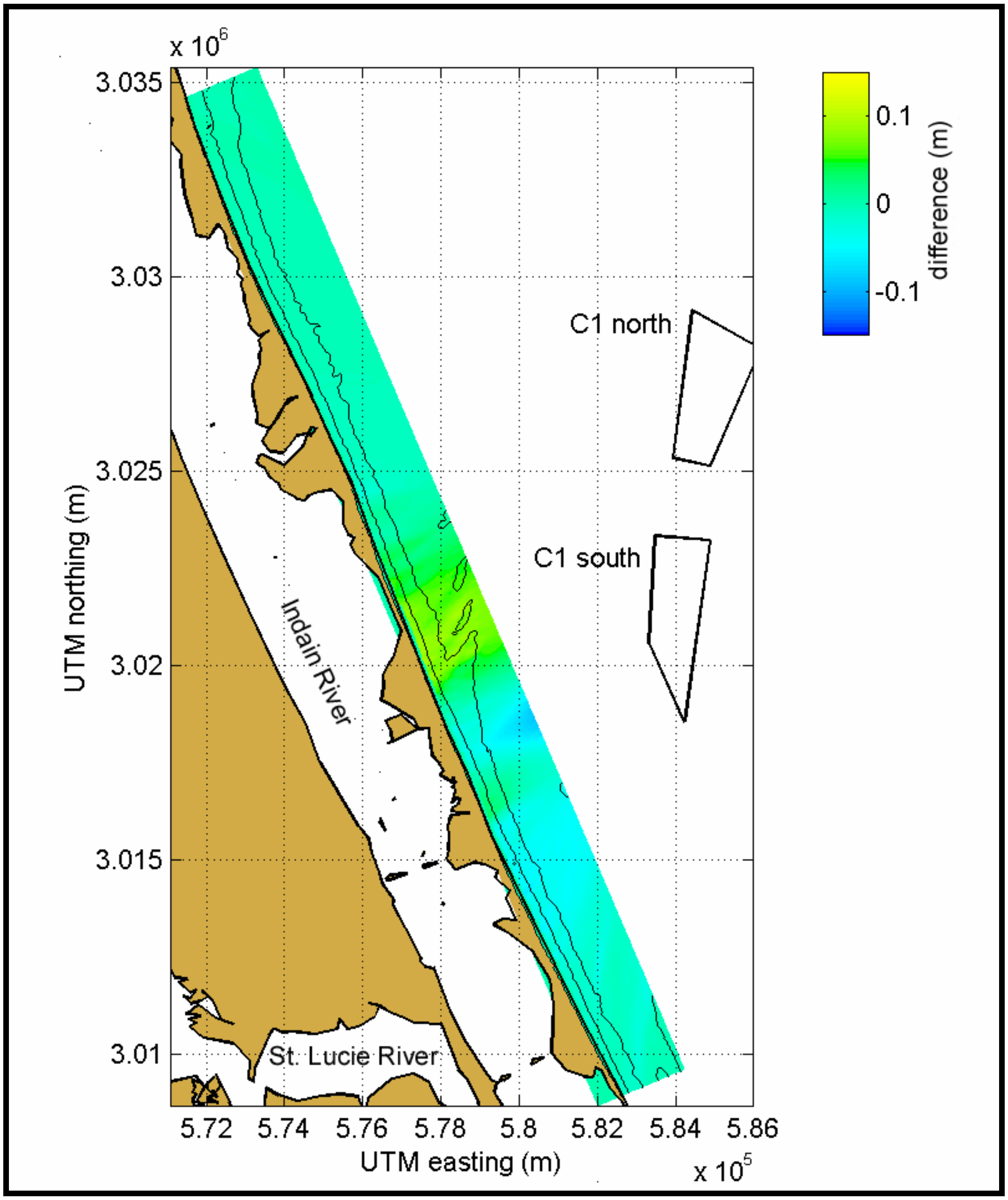

Figure 4-16. Wave height difference plot for fine grid model simulations offshore St. Lucie Inlet. Seafloor contours are shown at 5 m intervals.

4.2.1.1 Area A

Model output for existing conditions simulations offshore Cape Canaveral for wave Case 3A (Table 4-1) is presented in Figure 4-17. Canaveral Shoals, the complex of ridges and troughs that extend southeast from Cape Canaveral, caused significant increases in wave height as waves propagated over this area. As waves refracted around the shoals, wave heights increased by 0.5 m over offshore wave conditions. In the shoal field northeast of the Cape, wave heights increased by about 0.3 m above offshore wave heights. Wave direction changes also were observed in these areas.

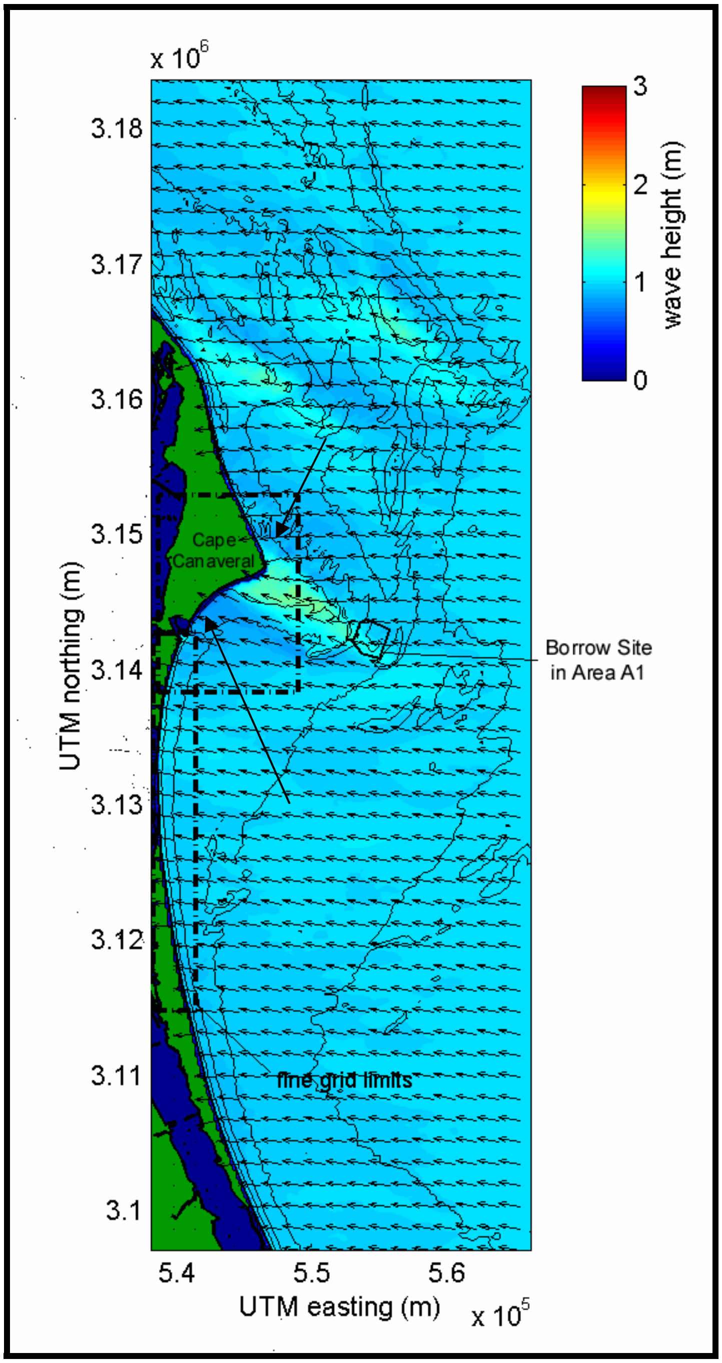

Figure 4-17. STWAVE output for wave modeling Area A, wave Case 3A (H_s = 1.0 m, T_{peak} = 7.7 sec, θ_{peak} = 100 deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. Seafloor contours are shown at 5 m intervals.

A greater degree of wave refraction was illustrated in model output for Case 6A (Figure 4-18). The offshore condition was a 1.6 m, 14.3 sec wave propagating from the east-northeast.

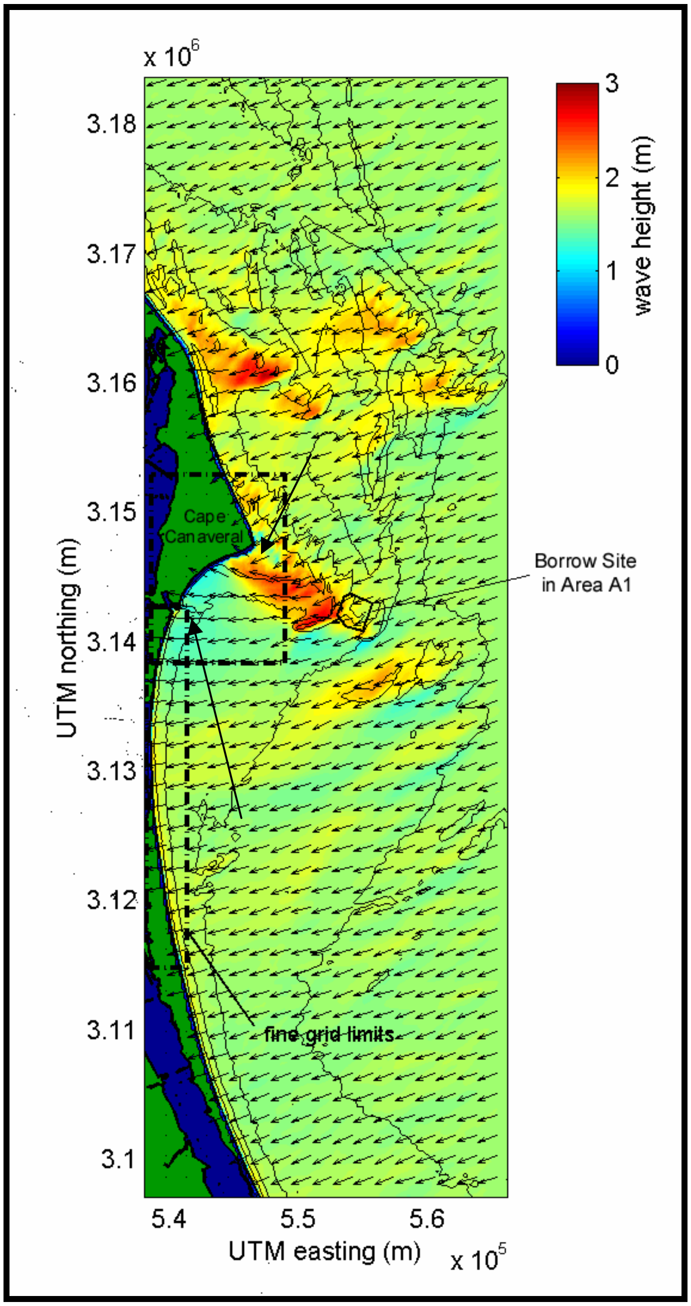

Figure 4-18. STWAVE output for wave modeling Area A, wave Case 6A (H_s = 1.6 m, T_{peak} = 14.3 sec, θ_{peak} = 65 deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. Seafloor contours are shown at 5 m intervals.

Vectors indicating wave direction illustrated that for some nearshore regions adjacent to the Cape, the direction of wave propagation changed more than 45 degrees, following the gradient in bathymetric contours. Largest waves in the model domain occurred at the shoals north of Canaveral Harbor (1.3 m higher than offshore waves). At shoals in the vicinity of the borrow site in Area A1, wave heights increased to a maximum of 2.8 m, 1.2 m above offshore conditions. Shoals tended to refract wave energy and caused focusing (wave convergence) near the Cape. However, the coast south of the Cape illustrated reduced wave heights (wave divergence).

Post-dredging wave height changes are illustrated in Figures 4-19 and 4-20 for Cases 3A and 6A, respectively. For Case 3A, maximum wave height increase resulting from dredging the borrow site was 0.2 m, and the maximum decrease in the shadow zone of the site was 0.3 m. The overall area of influence for this borrow site extended approximately 14 km north of the Cape to about 4 km south of Canaveral Harbor.

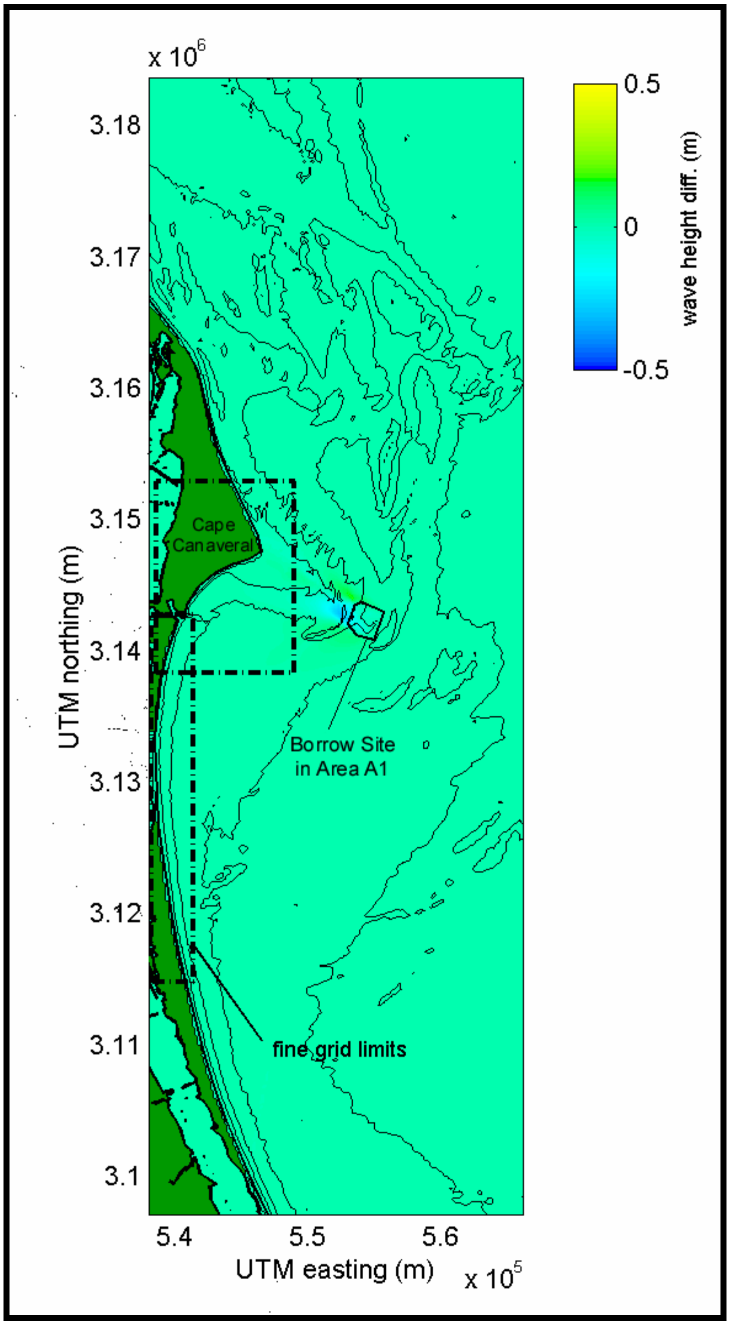

Figure 4-19. Wave height change between existing and post-dredging conditions at wave modeling Area A for STWAVE simulations, wave Case 3A ($H_s = 1.0$ m, $T_{peak} = 7.7$ sec, $\theta_{peak} = 100$ deg). Seafloor contours are shown at 5 m intervals.

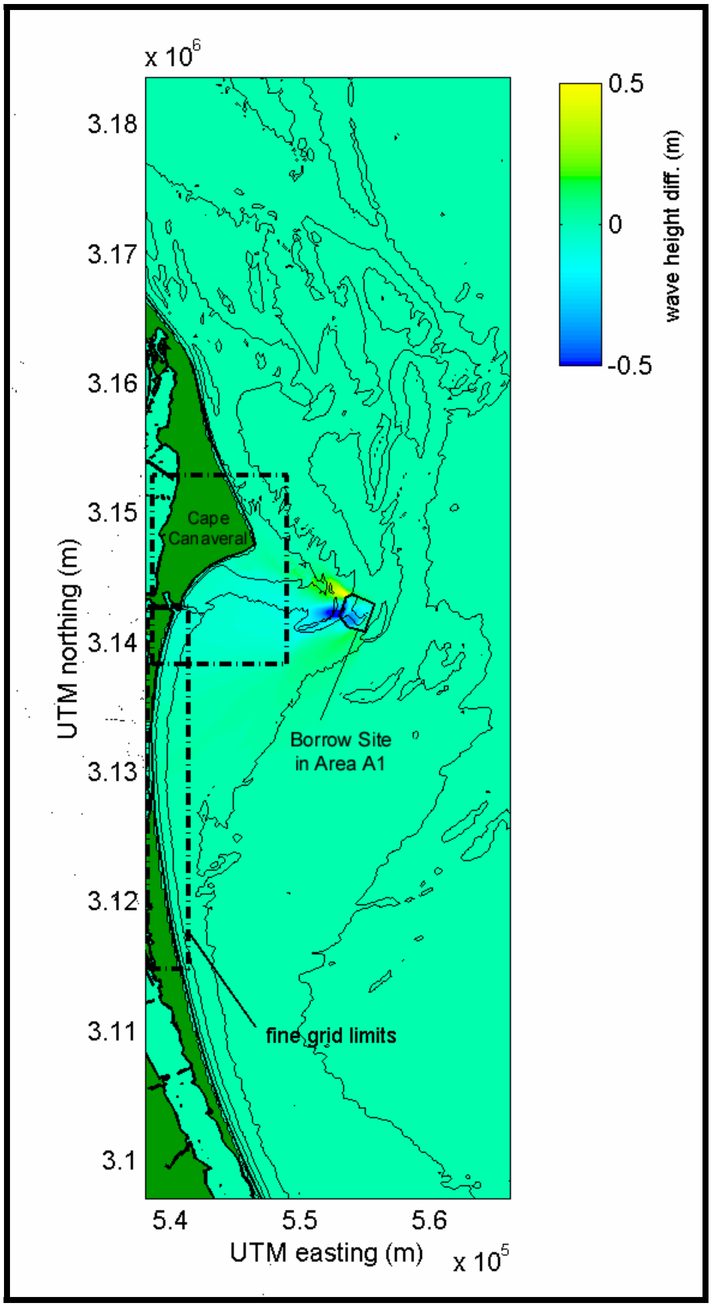

Figure 4-20. Wave height change between existing and post-dredging conditions at wave modeling Area A for STWAVE simulations, wave Case 6A (H_s = 1.6 m, T_{peak} = 14.3 sec, θ_{peak} = 65 deg). Seafloor contours are shown at 5 m intervals.

Similar wave difference results were illustrated for Case 6A (Figure 4-20). Maximum change in post-dredging wave heights was 0.7 m, substantially greater than change observed at other sites. The area of greatest wave height increase occurred at the northwest corner of the site. Wave heights did not increase by the same amount at the southwest corner, likely due to local bathymetry and geometry of the site. Deeper excavation depths at the northwest corner cause a greater degree of wave refraction. The longshore extent of influence was similar to that of Case 3A, but its location shifted slightly southward due to the direction of wave propagation.

4.2.1.2 Area B

Wave model output for offshore Sebastian Inlet at borrow sites in Areas B1 and B2 are illustrated in Figures 4-21 through 4-24. Figure 4-21 shows coarse grid results for wave Case 1B, a 1.9 m, 6.9 sec wave propagating from the NNE. Based on WIS results, waves from this direction occurred 2.3% of the time. For this relatively short period wave case, offshore bathymetry had a limited effect on the wave field as it propagated shoreward. The shoal encompassing the borrow site in Area B1 had the greatest influence on wave propagation in the region, although effects were small because the shoal had a minimum depth of approximately 12 m NGVD. Results from wave Case 10B are illustrated in Figure 4-22. This case had a similar wave height but longer peak period (H_s = 1.7 m, T_{peak} = 10.8 sec) than Case 1B. As such, wave refraction was greater and the influence of bottom features, like the shoal in Area B1, was more pronounced. Wave heights shoreward of the shoal were approximately 0.2 m greater than wave heights seaward of the feature.

Changes in the wave field caused by dredging at borrow sites in Areas B1 and B2 are shown for wave Cases 1B and 10B in Figures 4-23 and 4-24. To simulate borrow site dredging, bathymetry within each of the designated areas was lowered to an isobathic level. In effect, shoal relief was leveled to a constant elevation within each borrow site. Generally, less material was removed from the periphery of the site boundaries, and deeper dredging occurred near the center of the site. The difference plot in Figure 4-23 was computed by subtracting waves heights computed for existing conditions from those computed for post-dredging conditions. Therefore, negative differences indicated areas where wave height decreased after dredging occurred, and positive differences showed areas of increased height after dredging.

For wave Case 1B, borrow sites had a limited influence on waves over a long section of coast (>30 km), but changes on the order of 0.01 m occurred along 2.5 km of coast landward of the borrow site in Area B1 (Figure 4-23). At this borrow site, maximum change in wave height was approximately 0.10 m. Maximum change in wave height was approximately 0.12 m at the borrow site in Area B2. Even though the borrow site in Area B2 was smaller than that in Area B1 (i.e., less sediment dredged), B2 had a slightly greater impact on local wave heights. This apparent paradox is due to subtle changes in bathymetry relative to borrow site geometry.

The wave difference plot computed for wave Case 10B illustrates that changes to the wave field resulting from dredging at sand borrow sites in Areas B1 and B2 were more pronounced than for wave Case 1B (Figure 4-24). The length of shoreline influenced by changes in wave propagation from the two borrow sites was approximately 20 km; however, greatest changes (about 0.01 m) occurred within a 12 km stretch of coast. The zone of influence for this wave case illustrated two regions of increased wave height propagating from the lateral boundaries of the sites and a single zone of reduced heights at the shoreward boundaries. At B1, maximum changes in wave height were 0.13 m, very similar to those computed for the borrow site in Area B2. Although the magnitude of maximum wave height change for wave Case 10B was slightly larger than 1B, shoreline impacts associated with 10B were greater. Longer period waves of Case 10B were affected more by bathymetry in deeper water, causing larger areas of waves on the shoals to be impacted by dredging changes at borrow sites. This process resulted in a broader area of impacted shoreline.

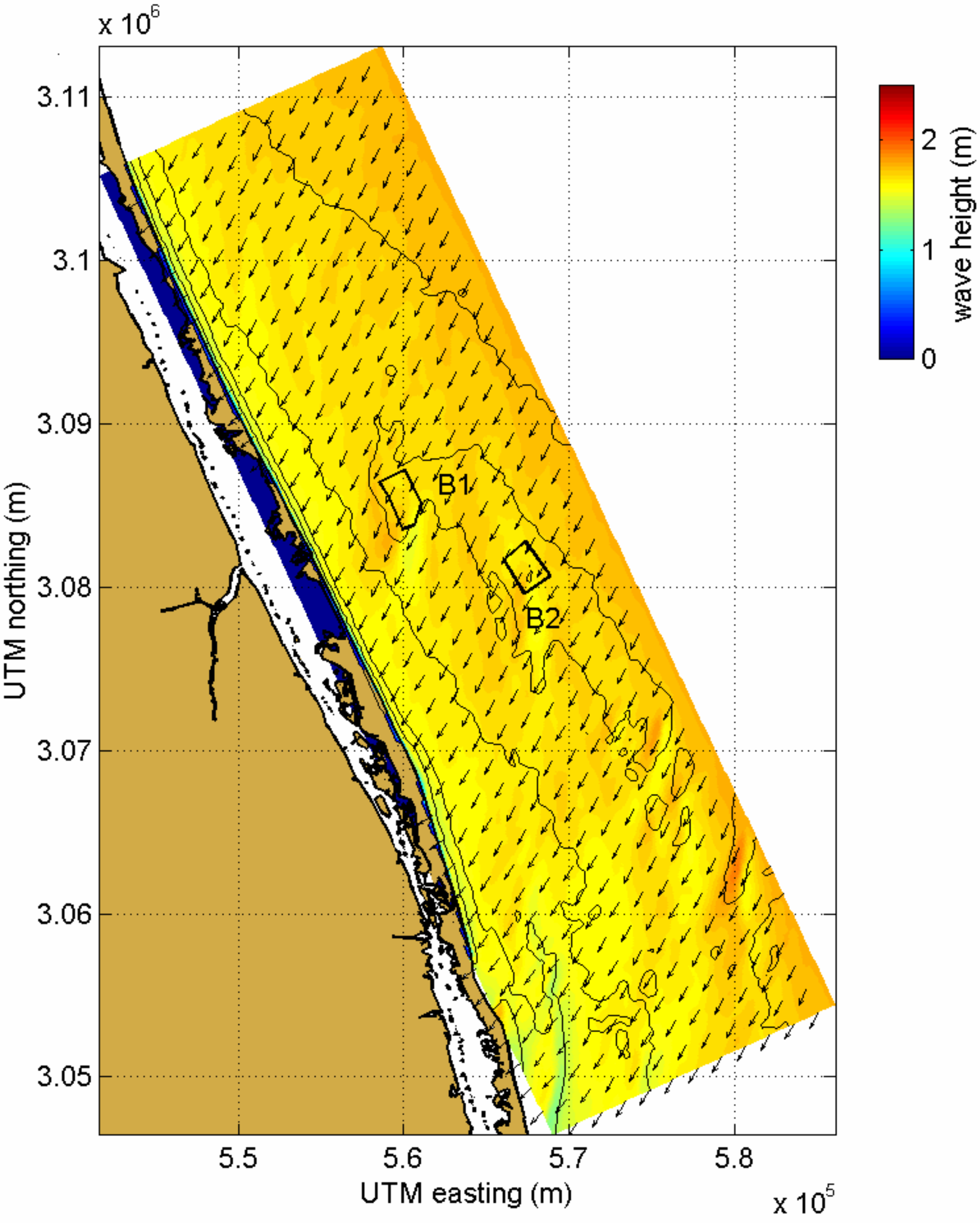

Figure 4-21. STWAVE output for wave modeling Area B, wave Case 1B (H_s = 1.9 m, T_{peak} = 6.9 sec, θ_{peak} = 25 deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. Seafloor contours are shown at 5 m intervals. B1 is the borrow site in Sand Resource Area B1, and B2 is the borrow site in Sand Resource Area B2.

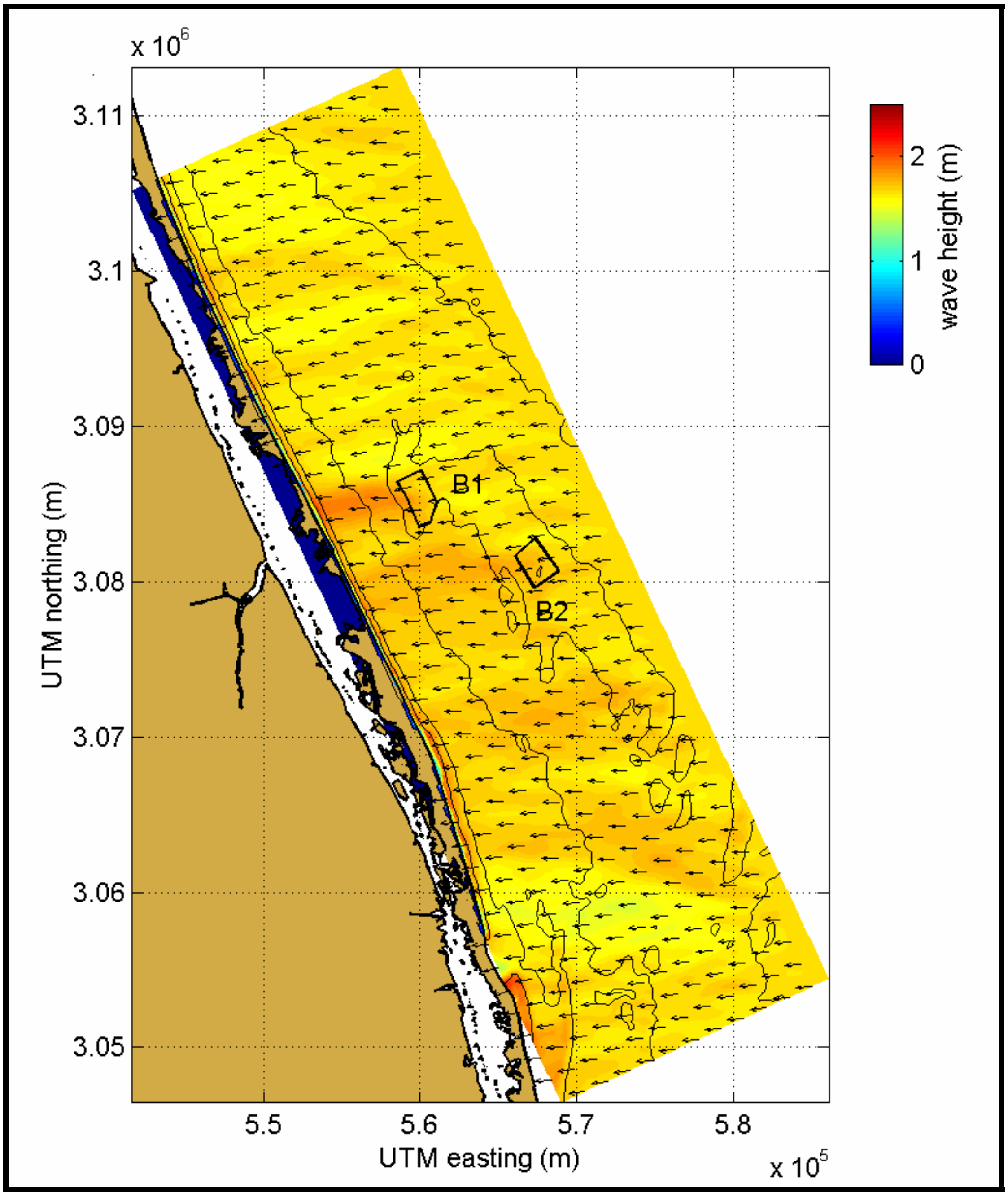

Figure 4-22. STWAVE output for wave modeling Area B, wave Case 10B (H_s = 1.7 m, T_{peak} = 10.8 sec, θ_{peak} = 90 deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. Seafloor contours are shown at 5 m intervals. B1 is the borrow site in Sand Resource Area B1, and B2 is the borrow site in Sand Resource Area B2.

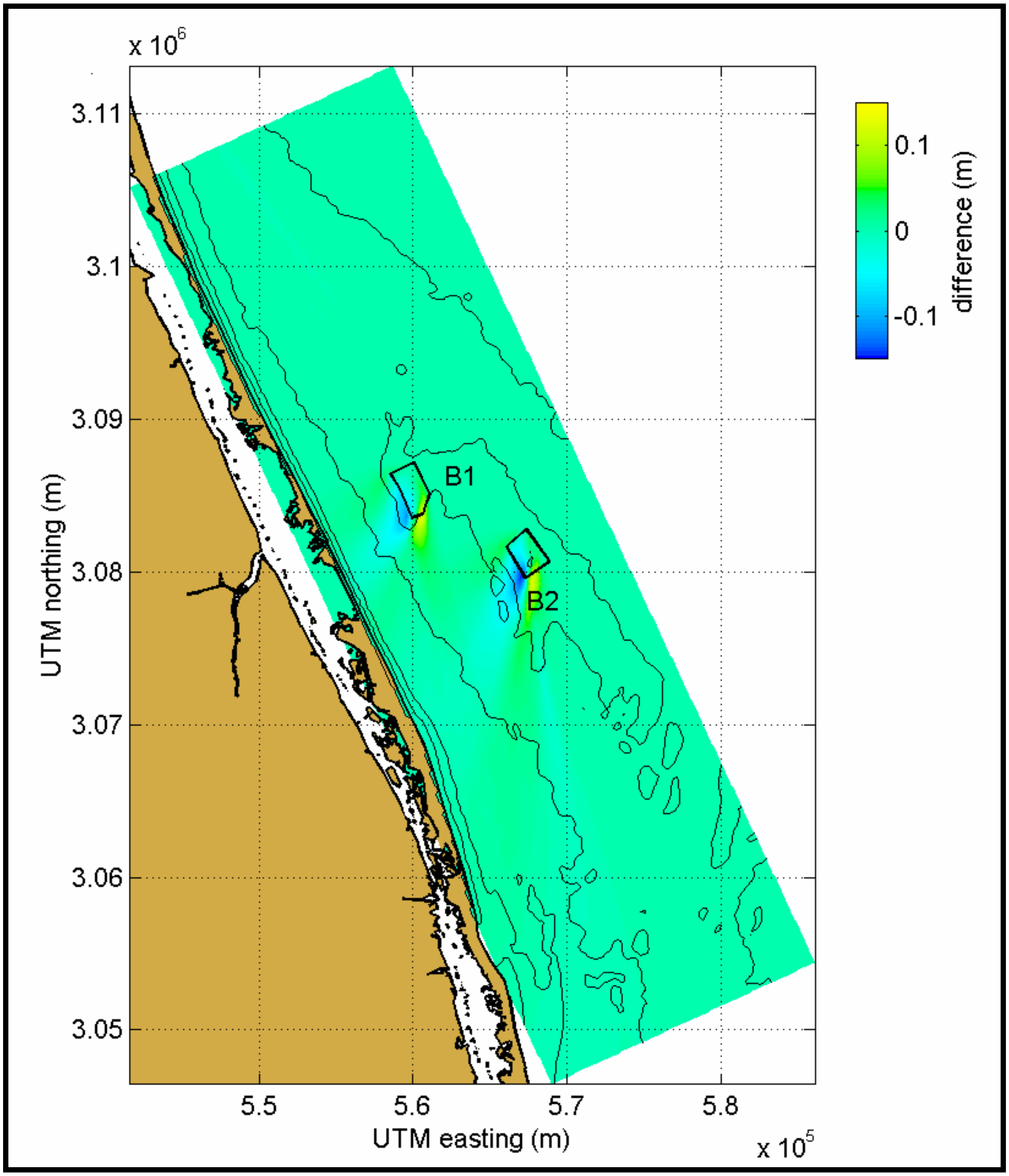

Figure 4-23. Wave height change between existing and post-dredging conditions at wave modeling Area B for STWAVE simulations, wave Case 1B (H_s = 1.9 m, T_{peak} = 6.9 sec, θ_{peak} = 25 deg). Seafloor contours are shown at 5 m intervals. B1 is the borrow site in Sand Resource Area B1, and B2 is the borrow site in Sand Resource Area B2.

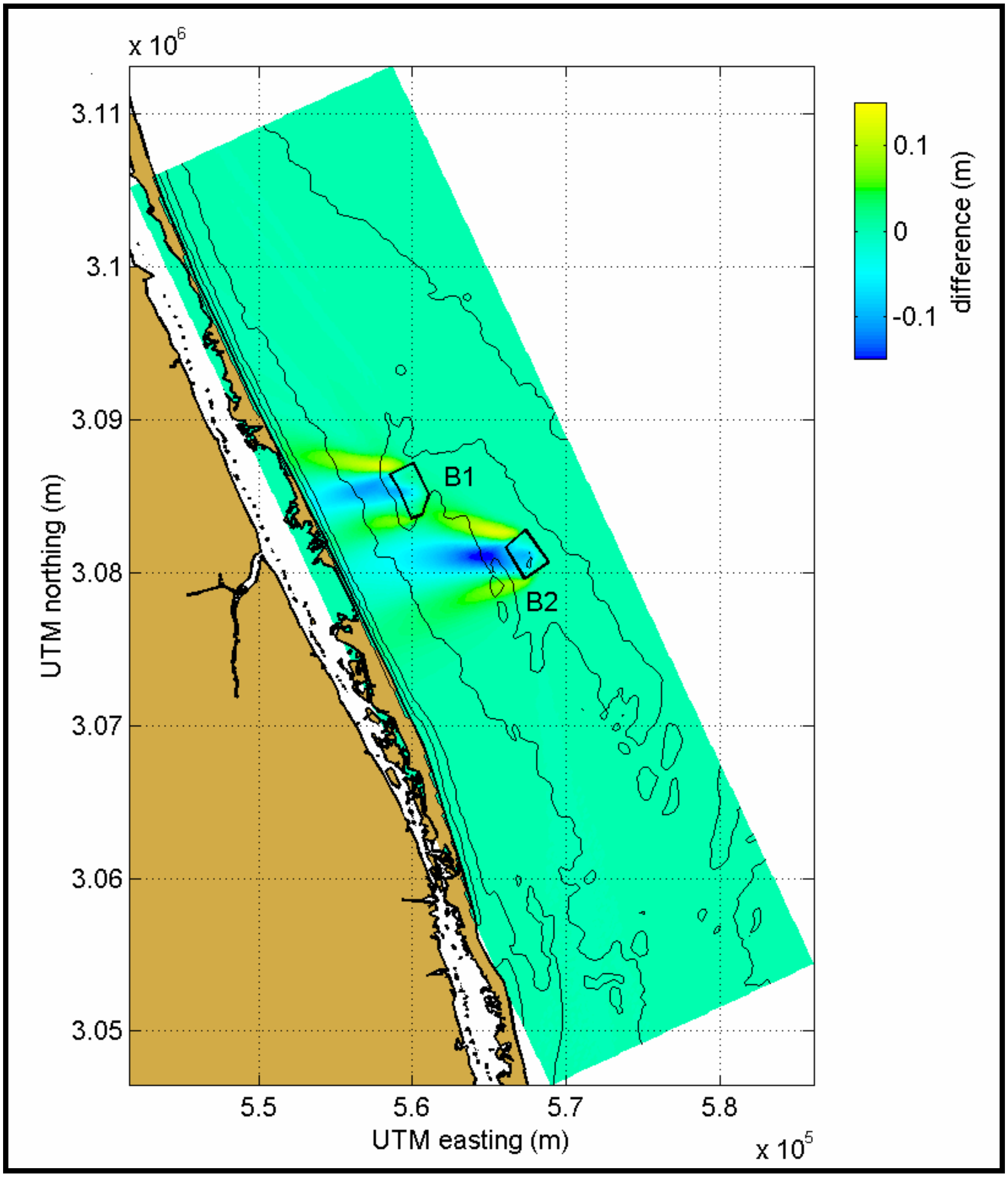

Figure 4-24. Wave height change between existing and post-dredging conditions at wave modeling Area B for STWAVE simulations, wave Case 10B (H_s = 1.7 m, T_{peak} = 10.8 sec, θ_{peak} = 90 deg). Seafloor contours are shown at 5 m intervals. B1 is the borrow site in Sand Resource Area B1, and B2 is the borrow site in Sand Resource Area B2.

4.2.1.3 Area C

Examples of wave model output for Area C borrow sites are shown in Figures 4-25 through 4-28. Figure 4-25 shows coarse grid results for wave Case 2C, a 1.5 m, 7.5 sec wave from the NE. For this case, slight wave focusing was identified at shoals within the designated borrow site boundaries. The minimum depth at C1 north was 7.6 m NGVD, and 5.4 m NGVD was the minimum depth at Site C1 south. Because shallower depths existed in these areas, waves passing over the shoals turned toward the shoreline sooner than in other areas the same distance offshore. Waves refracting over the shoals produced an area of increased wave heights landward of each shoal and a corresponding area of decreased wave heights immediately south of both sites. For the shoal within C1 north, maximum wave height increase was 0.18 m, and the maximum decrease was 0.39 m. Similar changes were observed at C1 south, where the maximum increase in wave height was 0.13 m and the maximum decrease was 0.33 m. Other features outside the two designated borrow sites affected waves in this region. A ridge centered at E 578400, N 3026200, approximately 3 km offshore, had a smaller impact on wave heights. Wave refraction over this shoal is potentially more significant than the impact to waves from shoals farther offshore because it is closer to shore and its area of influence is more focused along the shoreline.

For wave Case 10C, a 1.1 m, 11.1 second wave from the east (Figure 4-26), wave height changes at C1 north and C1 south were not as large as those for Case 2C, but wave energy was still focused behind the shoals. This focusing caused a zone of increased wave heights that extended to the shoreline. Unlike the results of Case 2C, where wave height changes at the borrow sites were more pronounced, the resulting wave shadow zone diffuses more as it approached the shoreline (due to the shorter peak wavelength of Case 2C).

The plot of wave height differences resulting from dredging Sites C1 north and C1 south are illustrated in Figure 4-27 for wave Case 2C. There seems to be a strong interaction between the two sites because C1 south is partially within the shadow zone of C1 north. The alignment of borrow sites caused a single area of increased wave heights at the shoreline (approximately 4 km long) and a more diffuse zone of reduced wave heights (extending 12 km toward St. Lucie Inlet). At the borrow sites, maximum wave height increase was 0.09 m, and the maximum wave height decrease was 0.15 m.

Wave height differences for wave Case 10C (Figure 4-28) illustrated that the borrow sites have an overlapping influence at the shoreline for waves propagating from the east, even though one site was not directly in the shadow of the other. The total length of affected shoreline was approximately 16 km. Wave height changes exhibited a typical impact pattern for two areas of increased wave heights flanked by a single area of reduced wave heights. Changes at the borrow sites were similar in magnitude to those for Case 2C. The resulting wave shadow zone for the two borrow sites was less diffuse due to a longer peak wavelength for this model case.

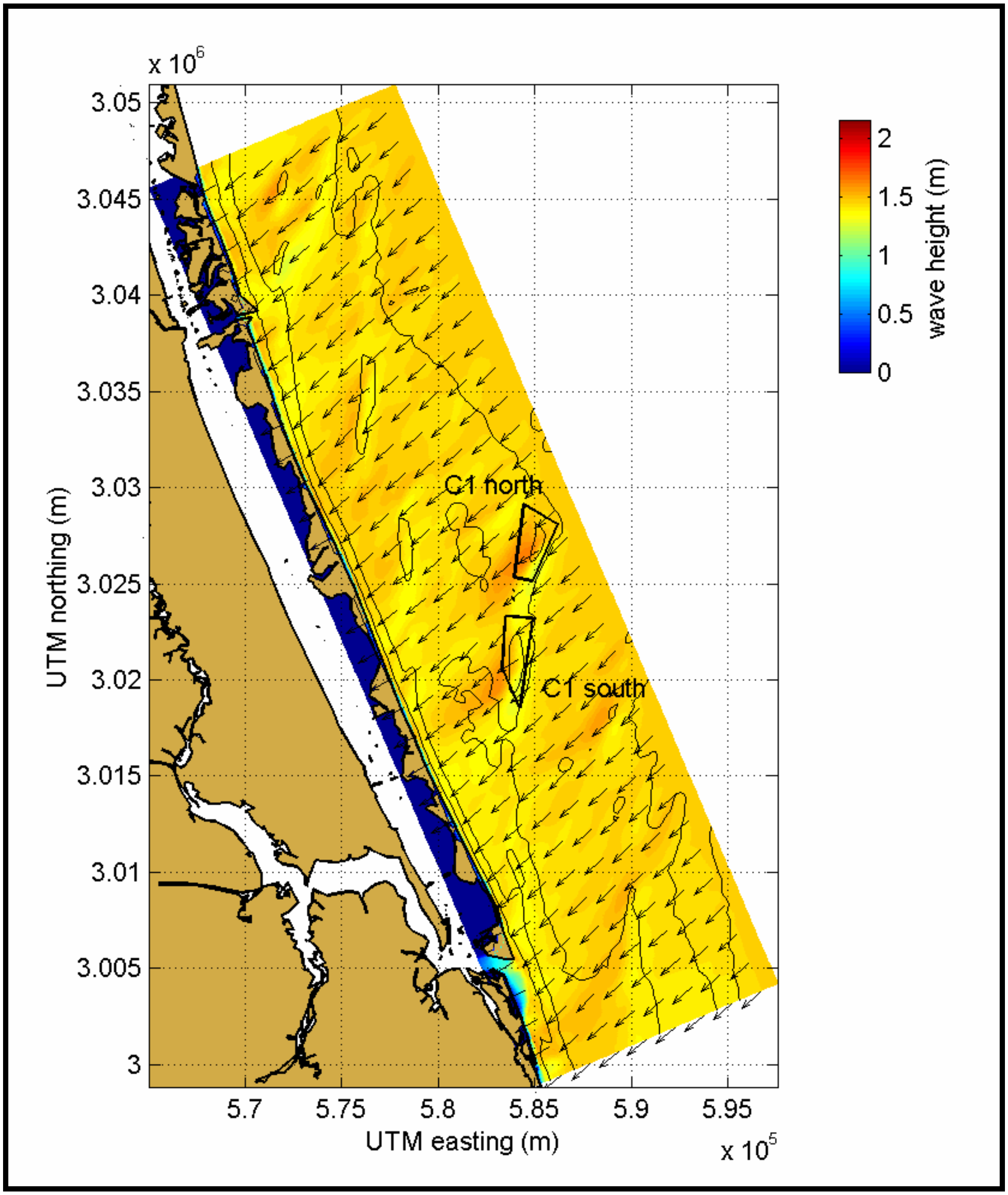

Figure 4-25. STWAVE output for wave modeling Area C, wave Case 2C (H_s = 1.5 m, T_{peak} = 7.5 sec, θ_{peak} = 47 deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. Seafloor contours are shown at 5 m intervals. C1 north and C1 south are the northern and southern borrow sites in Sand Resource Area C1.

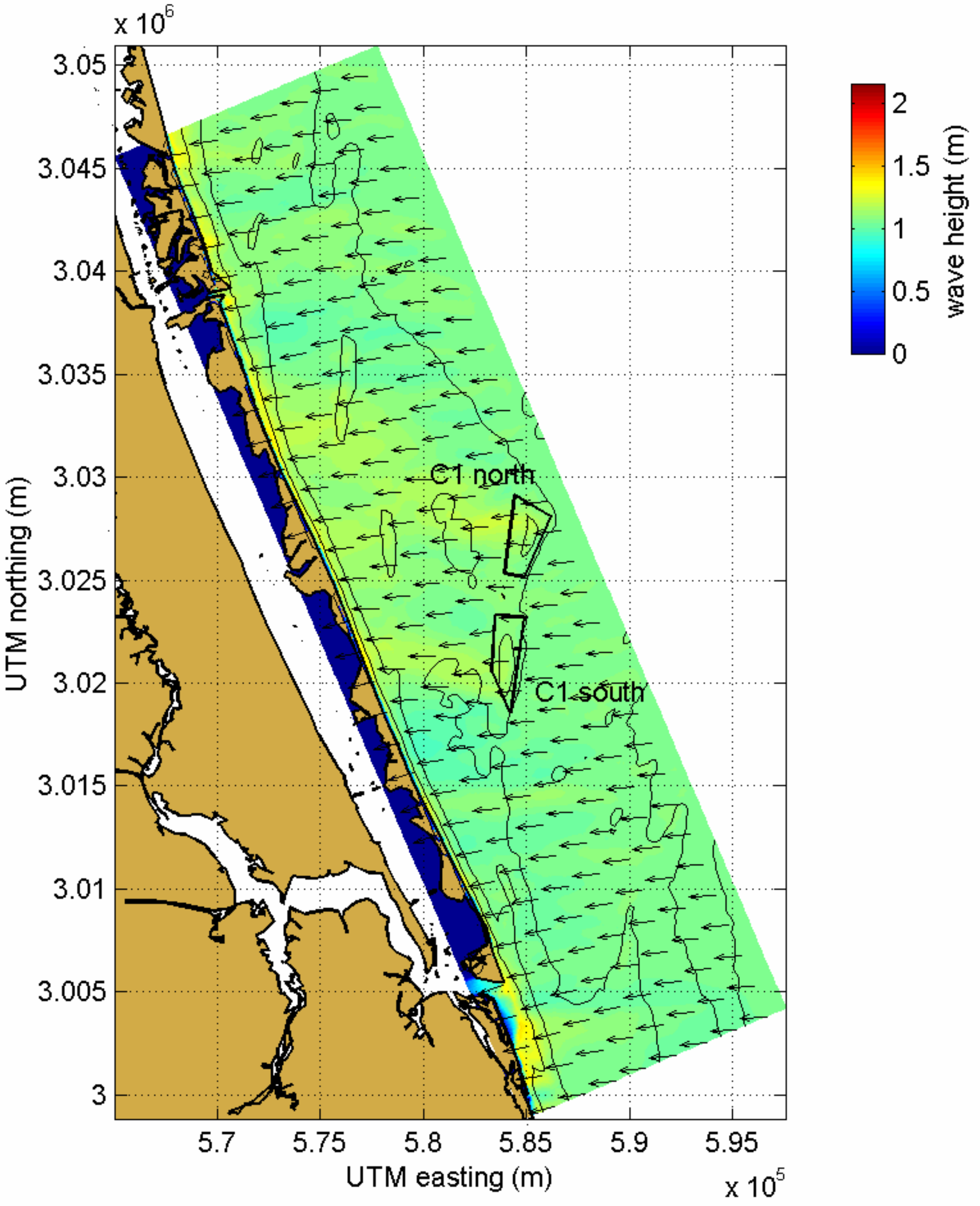

Figure 4-26. STWAVE output for wave modeling Area C, wave Case 10C (H_s = 1.1 m, T_{peak} = 11.1 sec, θ_{peak} = 87 deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. Seafloor contours are shown at 5 m intervals. C1 north and C1 south are the northern and southern borrow sites in Sand Resource Area C1.

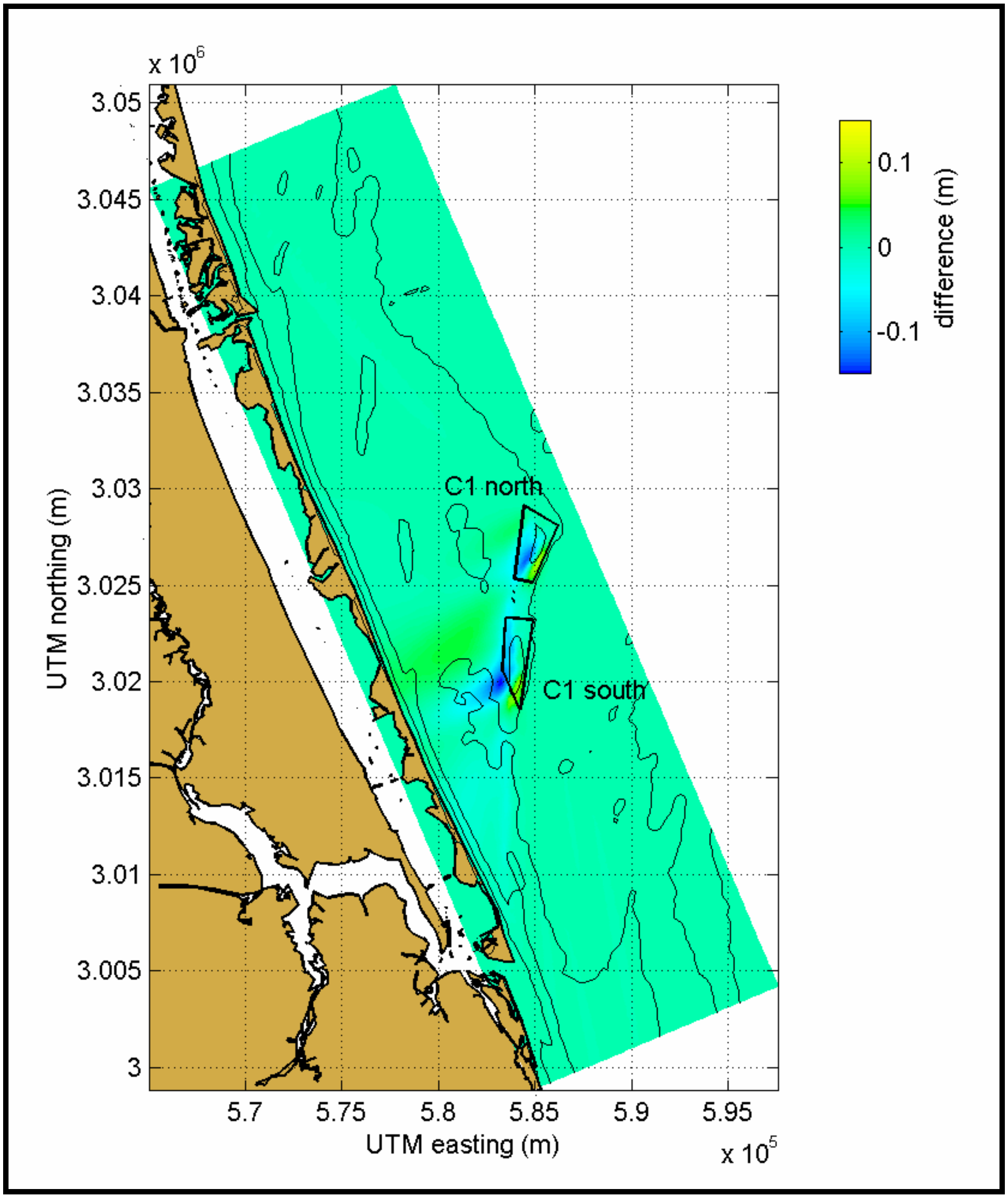

Figure 4-27. Wave height change between existing and post-dredging conditions at wave modeling Area C for STWAVE simulations, wave Case 2C (H_s = 1.5 m, T_{peak} = 7.5 sec, θ_{peak} = 47 deg). Seafloor contours are shown at 5 m intervals. C1 north and C1 south are the northern and southern borrow sites in Sand Resource Area C1.

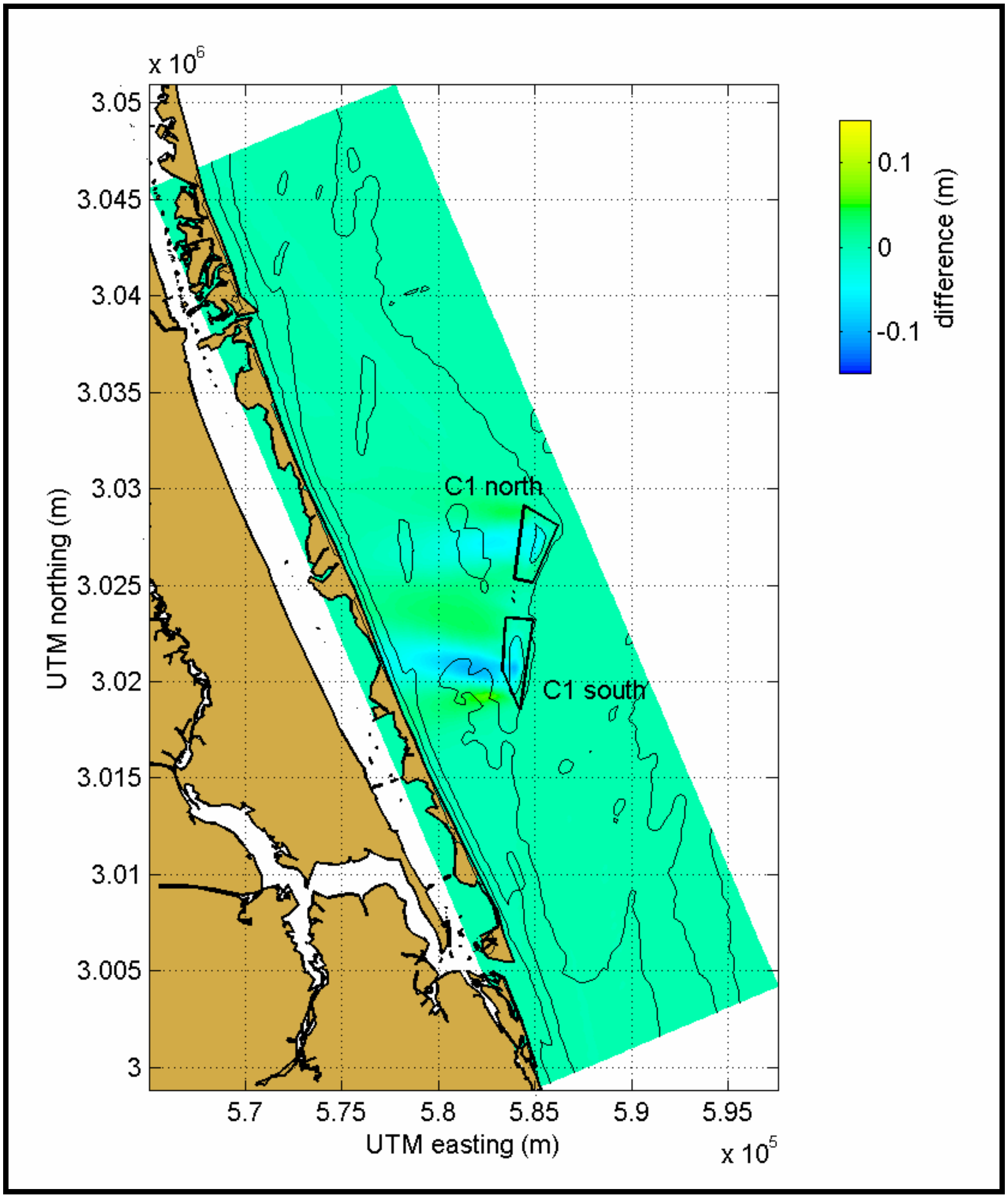

Figure 4-28. Wave height change between existing and post-dredging conditions at wave modeling Area C for STWAVE simulations, wave Case 10C (H_S = 1.1 m, T_{peak} = 11.1 sec, θ_{peak} = 87 deg). Seafloor contours are shown at 5 m intervals. C1 north and C1 south are the northern and southern borrow sites in Sand Resource Area C1.

4.2.1.4 Area D

Wave model output for Area D (Jupiter Inlet) is shown in Figures 4-29 through 4-32. Results from wave Case 1D, a 1.4 m, 6.9 sec wave from the NNE, are shown in Figure 4-29. The primary bathymetric feature in this region is a shoal area centered at E 595200, N 2987800, approximately 5.6 km offshore Jupiter Inlet. The shoal has a minimum water depth of 11.7 m NGVD. The borrow site designed for this area (D2) lies along the seaward margin of the shoal at the Federal-State boundary in relatively deep water. For wave Case 1D, the shoal influenced wave refraction patterns, resulting in a slight focusing of waves seaward of the shoal and an area of reduced wave heights 2.6 km along the shoreline north of Jupiter Inlet. Similar results were documented for wave Case 9D, a 1.3 m, 13.0 sec wave from the east-northeast (Figure 4-30). Wave heights increased behind the shoal, and a 4.9 km stretch of coastline north of Jupiter Inlet experienced increased wave heights. Maximum wave height increase caused by the shoal for Case 9D was 0.4 m, whereas Case 1D produced a 0.1 m change in wave height.

Wave height changes resulting from dredging Borrow Site D2 are documented in Figure 4-31. For wave Case 1D, the greatest change occurred at the north end of the site where the deepest excavation occurred. The maximum increase and decrease in wave height that resulted for this wave condition was 0.04 and 0.05 m, respectively. This small change relative to changes at borrow sites to the north was due to greater water depths at and seaward of Borrow Site D2.

For wave Case 9D, two shadow areas of reduced wave heights propagated from two separate areas within the borrow site, but join to form one shadow on the shoreward side of the shoal (Figure 4-32). This change pattern occurred because the original bathymetry within Site D2 contained two elevation peaks approximately 1.5 m higher than the surrounding shoal surface.

4.2.2 Sediment Transport Potential

Comparisons of average annual sediment transport potential were performed for existing and post-dredging conditions to document the relative impact of dredging at borrow sites on 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. Although largest changes to the wave field occur at a borrow site, impacts cannot be adequately assessed without determining the resulting impact to coastal processes at the shoreline. As an example, a large borrow site that causes a large change in wave height at the site, but is far offshore, could have less shoreline impact than a much smaller site located closer to shore.

The net sediment transport potential associated with average annual conditions (Tables 4-1 through 4-4) was computed for shorelines landward of proposed sand borrow sites. Transport potential was computed using fine grid model results. In addition to average annual results, wave model simulations and sediment transport potential calculations were performed for 20 individual years of WIS data to provide information necessary to develop a $\pm 0.5\sigma$ transport significance envelope. Wave modeling for 20 individual years proceeded in a similar fashion to the modeling effort for average annual conditions (i.e., wave data for each separate year was binned according to direction and period to develop several wave cases for each year). Results for Area A1 were based on an earlier form of the transport significance criterion. Application of this method used $\pm 1\sigma$ as the significance criterion based on splitting the 20-year wave-hindcast record into five 4-year periods as opposed to 20 individual. For this study, more than 1,000 individual wave model runs were completed to determine average annual conditions and associated transport significance envelopes.

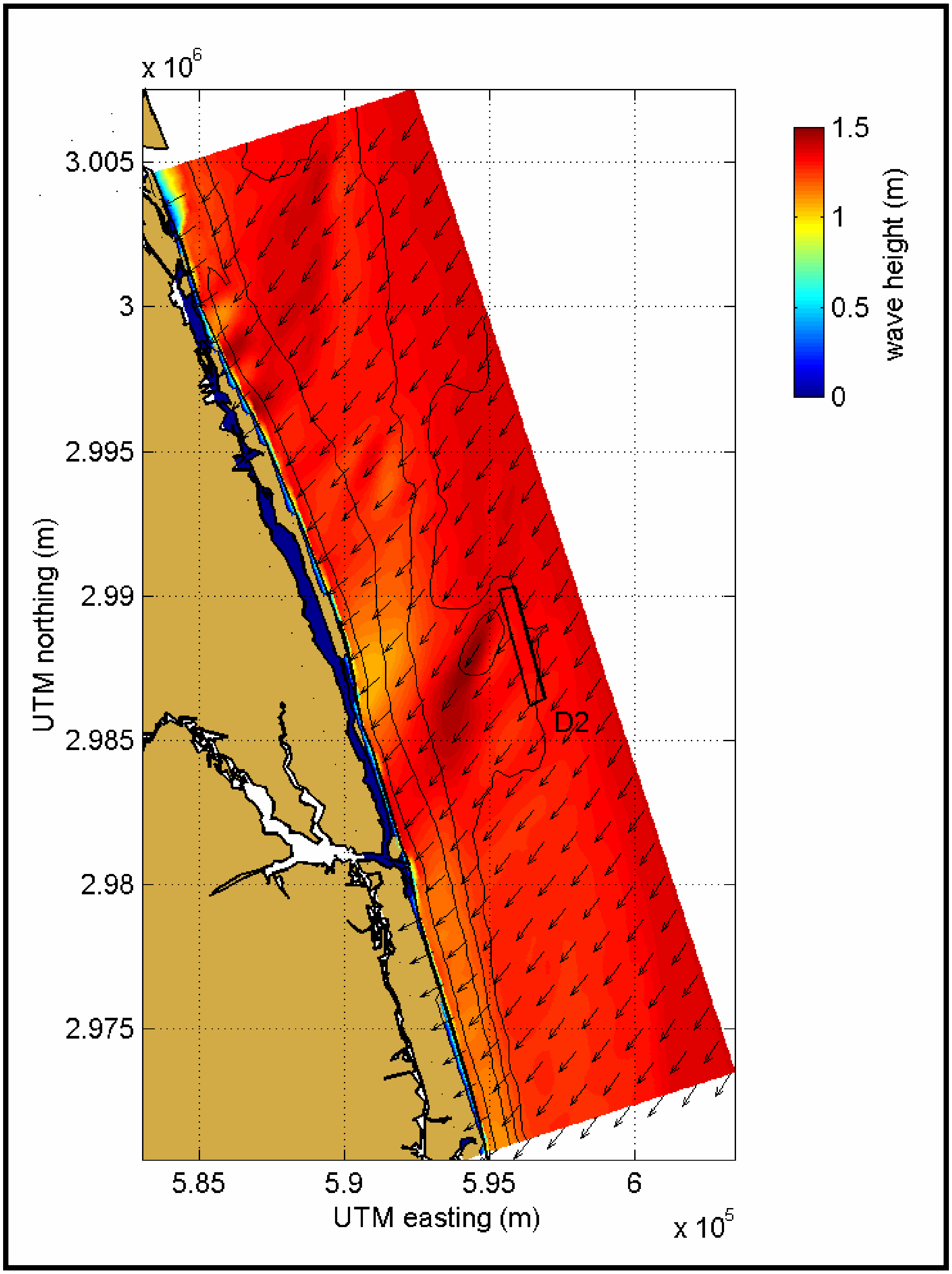

Figure 4-29. STWAVE output for wave modeling Area D, wave Case 1D (H_s = 1.4 m, T_{peak} = 6.9 sec, θ_{peak} = 32 deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. Seafloor contours are shown at 5 m intervals. D2 is the borrow site that extends from Sand Resource Area D1 into Sand Resource Area D2 along the Federal-State boundary.

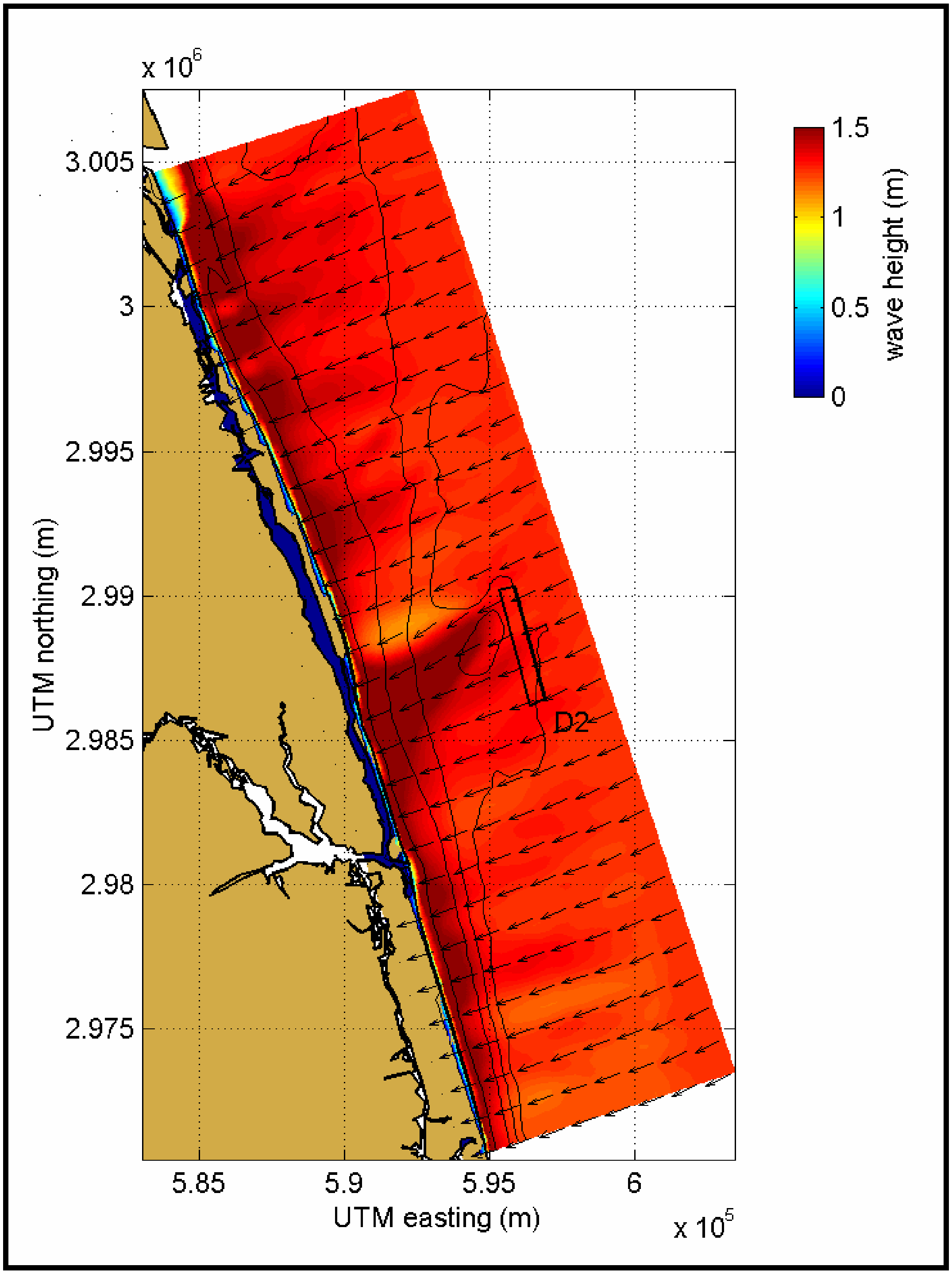

Figure 4-30. STWAVE output for wave modeling Area D, wave Case 9D (H_s = 1.3 m, T_{peak} = 13.0 sec, θ_{peak} = 62 deg). Color contours indicate wave height, and vectors show mean direction of wave propagation. Seafloor contours are shown at 5 m intervals. D2 is the borrow site that extends from Sand Resource Area D1 into Sand Resource Area D2 along the Federal-State boundary.

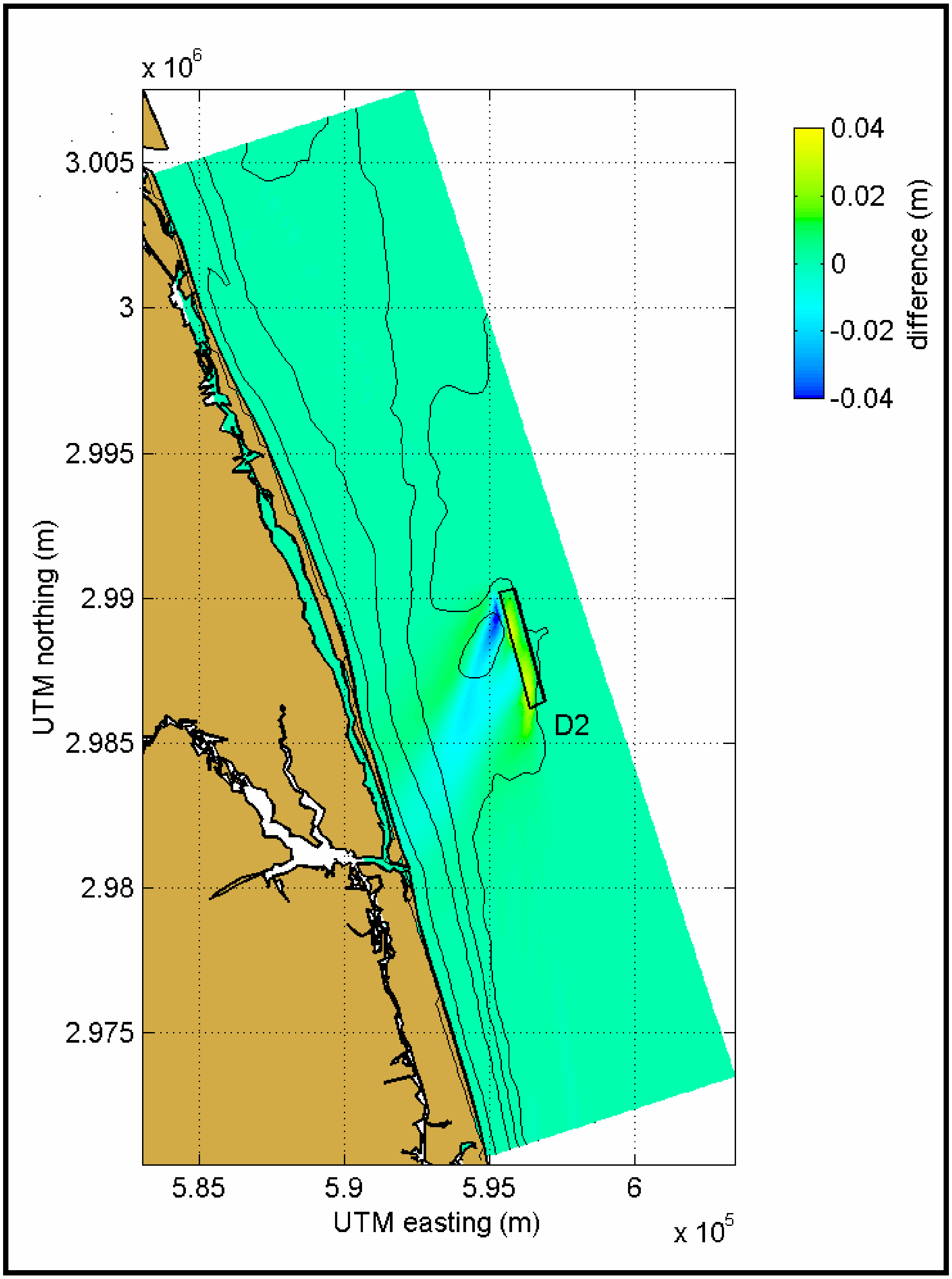

Figure 4-31. Wave height change between existing and post-dredging conditions at wave modeling Area D for STWAVE simulations, wave Case 1D (H_s = 1.4 m, T_{peak} = 6.9 sec, θ_{peak} = 32 deg). Seafloor contours are shown at 5 m intervals. D2 is the borrow site that extends from Sand Resource Area D1 into Sand Resource Area D2 along the Federal-State boundary.

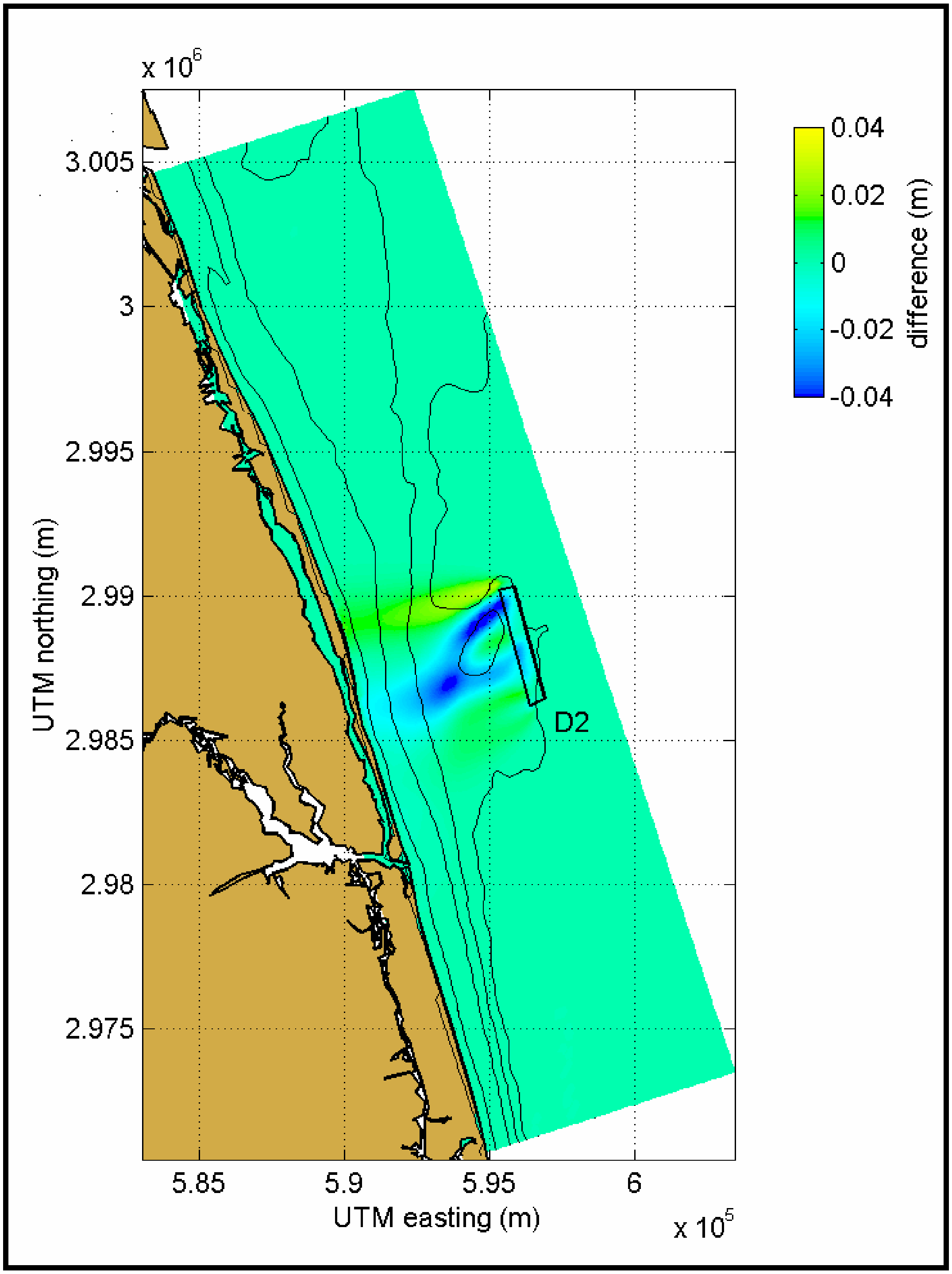

Figure 4-32. Wave height change between existing and post-dredging conditions at wave modeling Area D for STWAVE simulations, wave Case 9D (H_s = 1.3 m, T_{peak} = 13.0 sec, θ_{peak} = 62 deg). Seafloor contours are shown at 5 m intervals. D2 is the borrow site that extends from Sand Resource Area D1 into Sand Resource Area D2 along the Federal-State boundary.

Mean sediment transport potential calculated for Area A (adjacent to Cape Canaveral) for the modeled 20-year period is illustrated with computed transport curves of the 20 individual years used in the determination of the ±σ significance envelope (Figure 4-33). The shoreline south of Port Canaveral indicated strong net southerly transport of approximately 500,000 m^3/yr, which gradually reduced to approximately 300,000 m^3/yr at the southern limit of the model grid. The significance envelope was largest (approximately ±300,000 m^3/yr) north of Cape Canaveral and in the southern half of the modeled area, and it reduced to approximately ±50,000 m^3/yr just north of Port Canaveral. The relatively small significance envelope for this section of shoreline suggested that inter-annual variability of mean sediment transport was small due to the sheltering effect of Cape Canaveral and Canaveral Shoals.

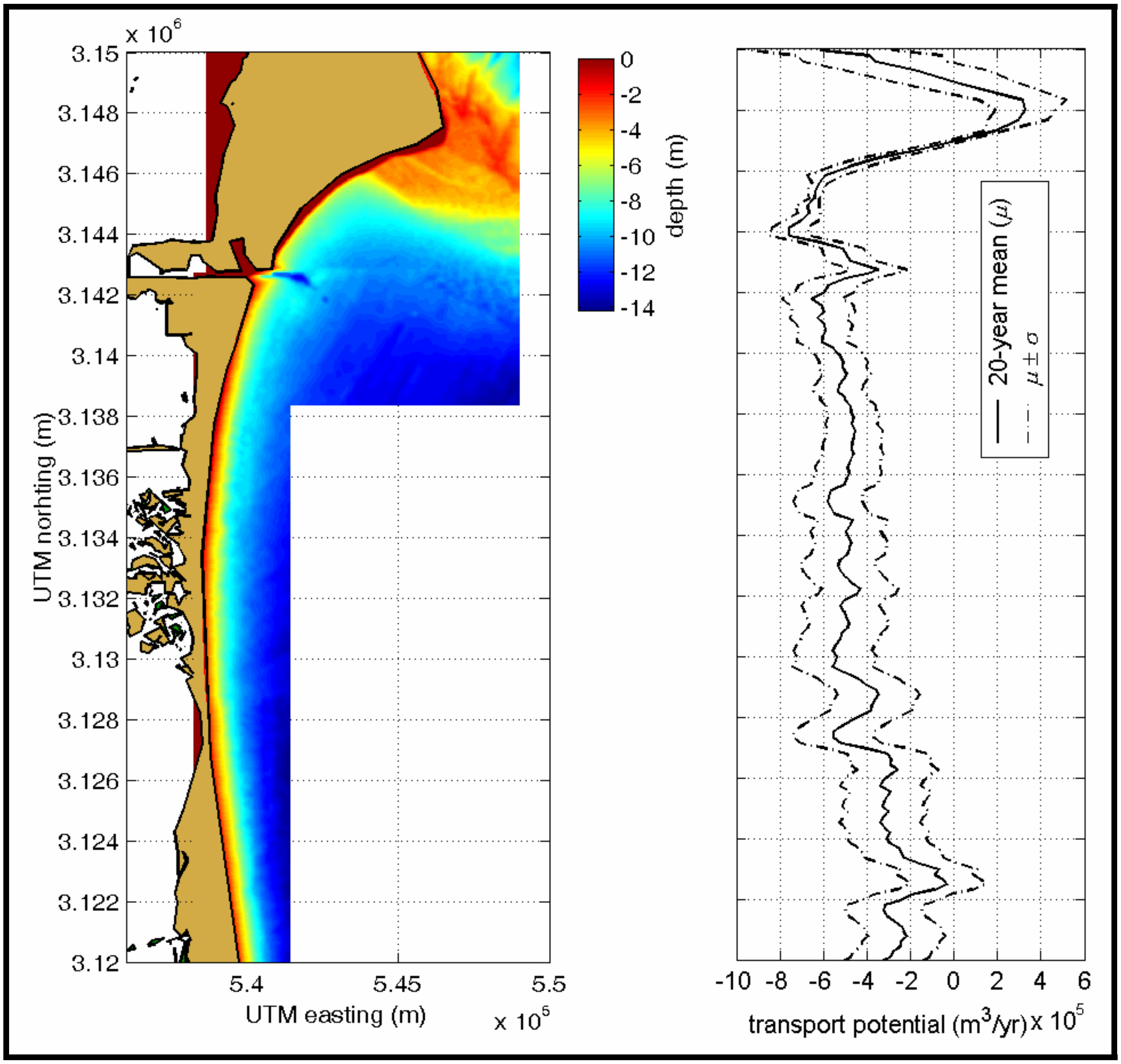

Figure 4-33. Average annual sediment transport potential (solid black line) computed for the shoreline landward of the borrow site in Area A1 (Port Canaveral). Positive transport potential is directed to the north and negative transport potential is directed to the south. The black dot-dash lines indicate the ±σ significance envelope about the mean net transport rate.

Average annual results for modeled Area A documented gross northerly- and southerly-directed transport potential (Figure 4-34), with average net transport, for the 20-year modeled period. The modeled shoreline generally had a strong south-oriented transport potential between the cusp of Cape Canaveral and Port Canaveral. Between Port Canaveral and the southern limit of the grid, potential transport gradually became less southerly dominated, with gross northerly transport rates (~200,000 m^3/yr) that were roughly half of gross southerly transport rates.

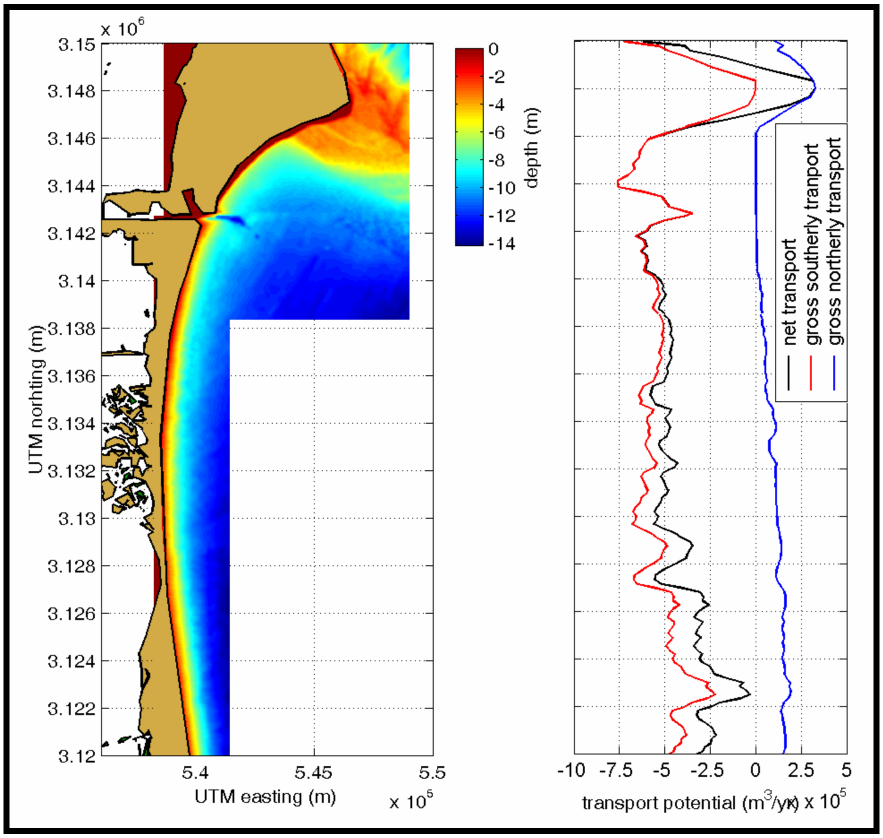

Figure 4-34. Average net transport potential (black line) with gross southerly- and northerly-directed transport potential (red and blue lines, respectively) for the shoreline landward of Area A1.

Mean transport potential computed for Area B for the modeled 20-year period is shown with computed transport curves for the 20 individual years used to determine the ±0.5σ significance envelope (Figure 4-35). Results indicated that along the coastline from N 3,090,000 to N 3,065,000, net transport potential was generally less than 100,000 m^3/yr to the south. There was an approximate ±500,000 m^3/yr range in annual net transport rates. Along this shoreline, results indicated that it was possible in some years for net transport potential to be northward directed. South of N 3,065,000, net transport potential was to the south at around 500,000 m^3/yr. This may be due to a change in shoreline orientation that occurred at this point. The annual variation in net transport potential was similar (approximately ±500,000 m^3/yr) for the shoreline north of the break. For the length of modeled shoreline, the year with greatest modeled southerly transport was 1980, and the year with greatest northerly transport was 1990.

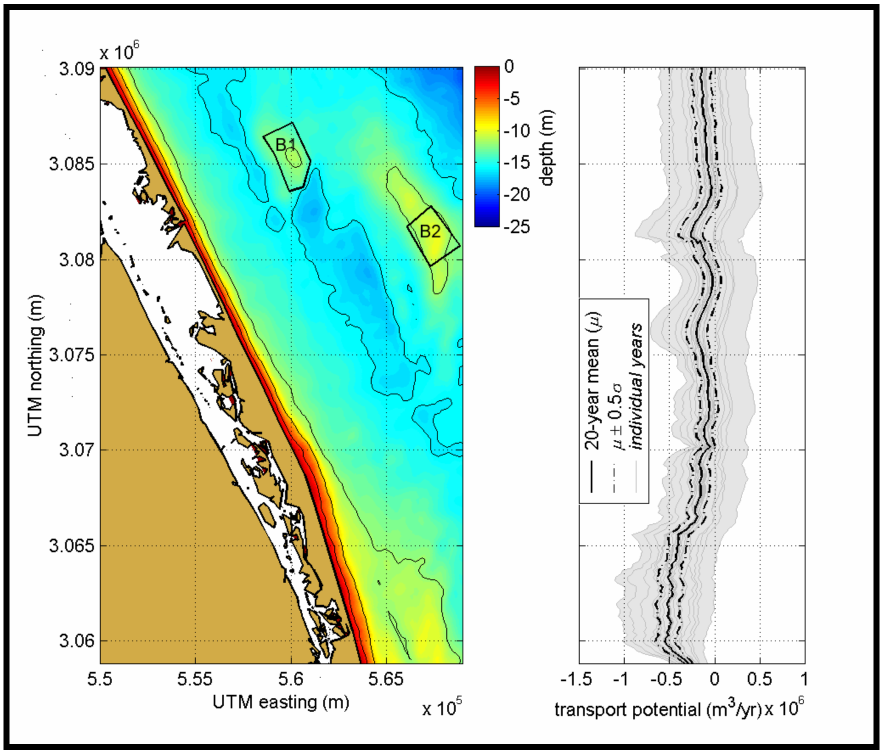

Figure 4-35. Average annual sediment transport potential (solid black line) computed along the shoreline landward of borrow sites in Areas B1 and B2 (Sebastian Inlet). Positive transport potential is directed to the north and negative transport potential is directed to the south. Net transport potential curves determined for 20 individual years of WIS data are indicated by the gray shaded area. The ±0.5σ significance envelope (black dot-dash lines) about the mean net transport rate was determined using the 20 net potential curves. B1 is the borrow site in Sand Resource Area B1, and B2 is the borrow site in Sand Resource Area B2.

Average annual results for modeled Area B show the breakdown of gross northerly- and southerly-directed transport potential (Figure 4-36), with average net transport, for the 20-year modeled period. The modeled shoreline generally had bi-directional transport of approximately 400,000 m^3/yr, which resulted in a much smaller net potential, directed to the south. South of N 3,065,000, north-directed transport decreased and south-directed transport increased. The result was an increase in net transport to the south.

Computed mean annual transport potential for modeled Area C was to the south, ranging from approximately 400,000 m^3/yr at the northern boundary of the study area to approximately 100,000 m^3/yr at the southern limit near St. Lucie Inlet (Figure 4-37). Sand transport potential calculations for 20 individual years indicated that the annual variability in transport potential had a range of approximately ±400,000 m^3/yr to the north that gradually decreases to approximately ±200,000 m^3/yr at the southern limit of the modeled area. Along some sections of the modeled shoreline, it was possible to have net northerly-directed transport during some of the years. Similar to the results for Area B, the year with greatest modeled southerly transport was 1980, and the year with greatest northerly transport was 1990. For the mean transport curve, there was a local minimum that occurred at N 3026500. This likely resulted from the presence of the shoal ridge centered at E 578400 N 3026200, approximately 3 km offshore.

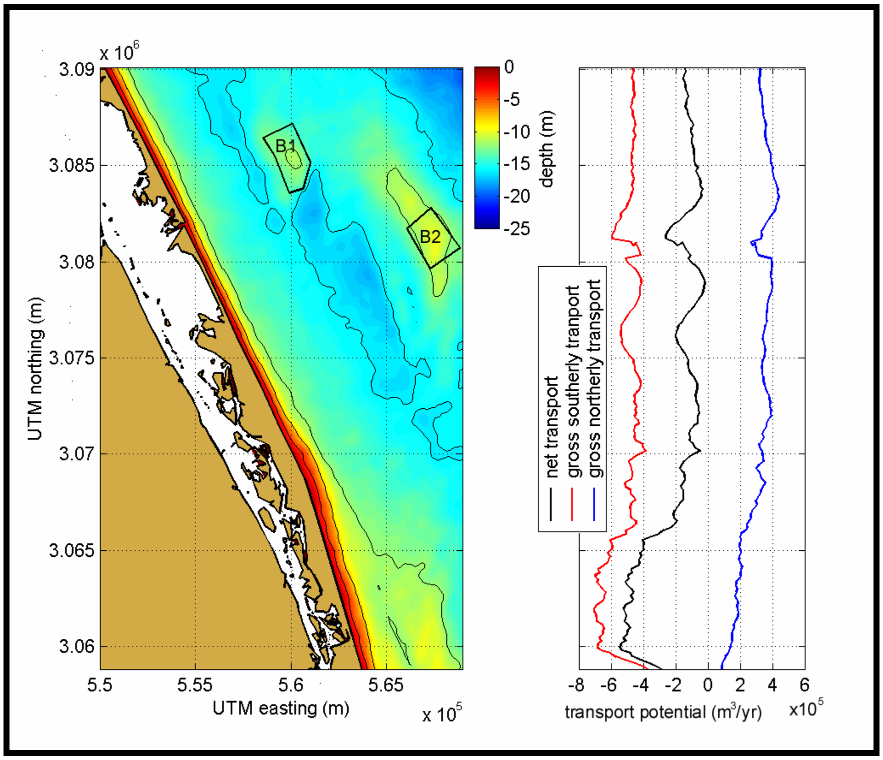

Figure 4-36. Annual net transport potential (black line) with gross southerly- and northerly-directed transport (red and blue lines, respectively) for the shoreline landward of B1 and B2. B1 is the borrow site in Sand Resource Area B1, and B2 is the borrow site in Sand Resource Area B2.

Average annual results for modeled Area C showed the breakdown of gross northerly- and southerly-directed transport potential (Figure 4-38), with the average net transport, for the 20-year modeled period. The transport potential along this shoreline was more strongly to the south than for Area B. Toward St. Lucie Inlet, transport potential becomes more bi-directional, as there was a decrease in gross southerly transport and an increase in gross northerly transport potential.

Net transport along the coastline landward of Area D (Jupiter Inlet) varied from about 200,000 m^3/yr to the south near the northern limit of the area to about 500,000 m^3/yr to the south near Jupiter Inlet (Figure 4-39). Results from the 20 individual modeled years showed that the annual variability ranged from approximately ±150,000 m^3/yr in the northern part of Area D to approximately ±300,000 m^3/yr at the southern extent of the model grid. At it greatest, net transport potential varied by about ±500,000 m^3/yr near N 2985000 (gray shaded area on Figure 4-39). Similar to modeled Areas B and C, the year with greatest modeled southerly transport was 1980, and the year with greatest northerly transport was 1990. As with the entire study area, net transport potential was always to the south. The large acceleration in south-directed transport between N 2,988,000 and N 2,986,000 indicated that the area between these locations was highly erosional. Historical data indicate that an erosional hot spot existed in this area (see Ramsey et al., 1995). Severe beach erosion has been a problem in the area called the "S" curve (N 2,987,600) where a north-south coastal roadway was diverted landward due to pervasive erosion.

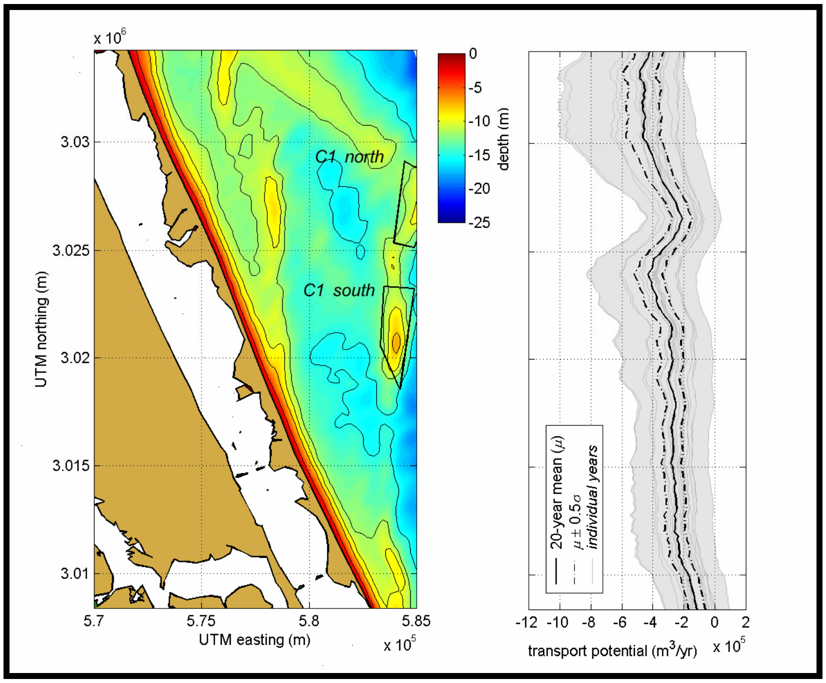

Figure 4-37. Average annual sediment transport potential (solid black line) computed along the shoreline landward of Borrow Sites C1 north and C1 south. Positive transport potential is directed to the north and negative transport potential is directed to the south. Net transport potential curves determined for 20 individual years of WIS data are indicated by the gray shaded area. The ±0.5σ significance envelope (black dot-dash lines) about the mean net transport rate was determined using the 20 net potential curves. C1 north and C1 south are the borrow sites in Sand Resource Area C1.

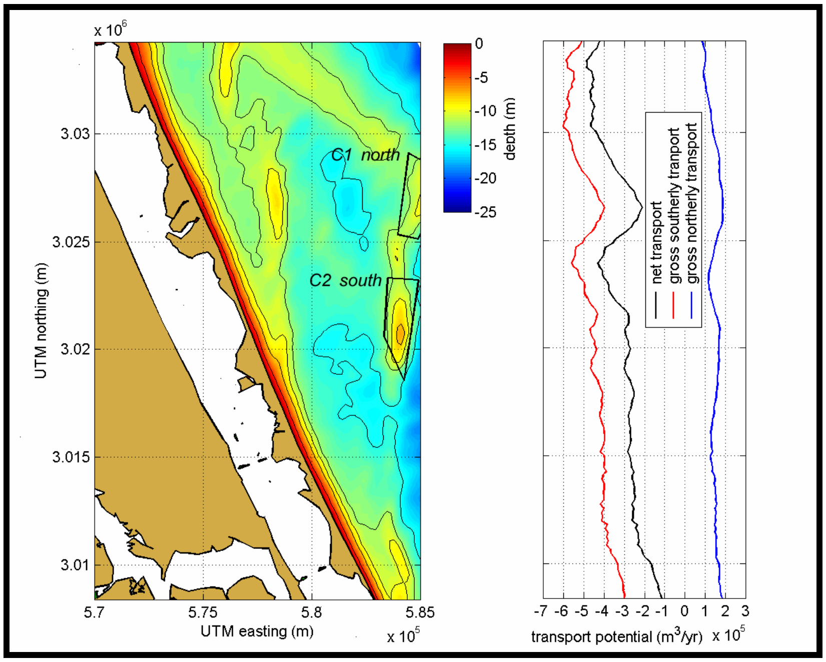

Figure 4-38. Annual net transport potential (black line) with gross southerly- and northerly-directed transport (red and blue lines, respectively) for the shoreline landward of C1 north and C1 south. C1 north and C1 south are the borrow sites in Sand Resource Area C1.

Results illustrated in Figure 4-40 document that the transport potential was strongly to the south. North of the “S” curve, gross northerly transport potential was approximately 100,000 m^3/yr. South of this area, north-directed transport was almost zero, resulting in unidirectional transport to the south.

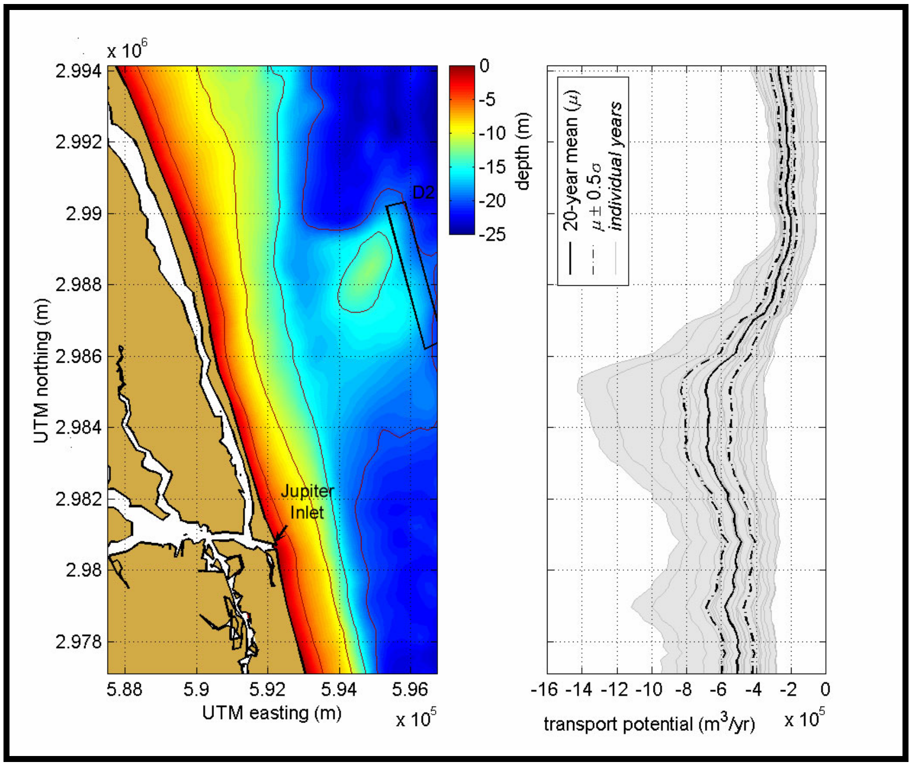

Figure 4-39. Average annual sediment transport potential (solid black line) computed along the shoreline landward of Borrow Site D2. Positive transport potential is directed to the north and negative transport potential is directed to the south. Net transport potential curves determined for 20 individual years of WIS data are indicated by the gray shaded area. The ±0.5σ significance envelope (black dot-dash lines) about the mean net transport rate was determined using the 20 net potential curves. D2 is the borrow site in between Sand Resource Areas D1 and D2.

4.2.2.1 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 provided a semi-quantitative method for determining whether a) wave-induced longshore transport was responsible for observed shoreline change, and b) long-term shoreline change trends were consistent with shorter time-period (20-year) sediment transport potential analyses. 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 in sediment transport. Simply expressed, this relationship is

$$\frac{\partial Q}{\partial y} \propto \frac{\partial x}{\partial t} \qquad (4.10)$$

where *Q* is sediment transport, *y* is alongshore distance, *x* is 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. The gradient in sediment transport potential was not expected to perfectly simulate this process, but good general agreement between these two quantities would suggest that the transport potential model reasonably represented long-term coastal processes for a given area, and thus, the model's ability to predict likely impacts that may 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 provided a without-project assessment of shoreline response for comparison with predicted changes in wave-energy focused at the shoreline resulting from potential offshore sand dredging activities. Because continuous measurements of historical shoreline change are available at 50-m alongshore intervals (see Section 3.0), 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.

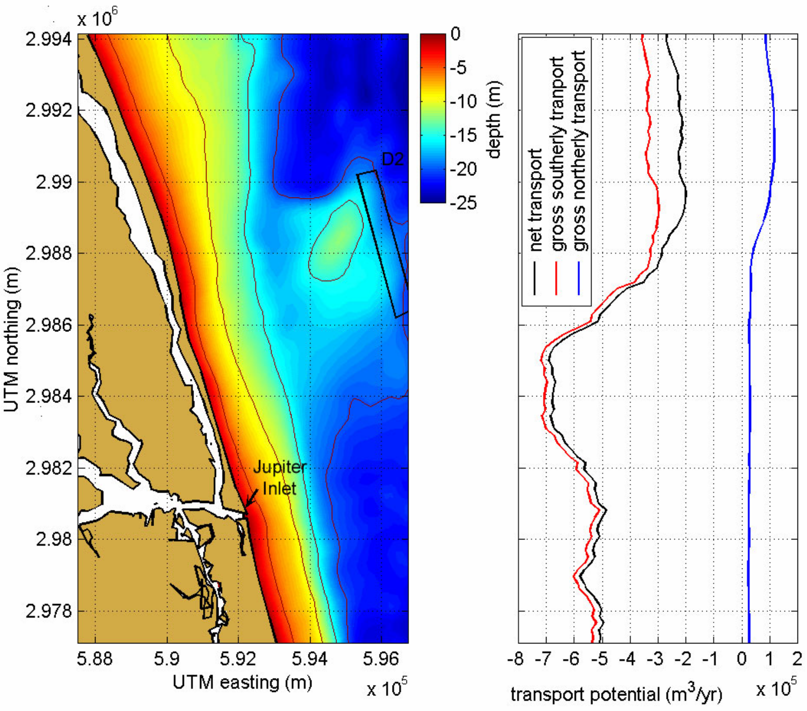

Figure 4-40. Annual net transport potential (black line) with gross southerly- and northerly-directed transport (red and blue lines, respectively) for the shoreline landward of the borrow site in modeled Area D. D2 is the borrow site between Sand Resource Areas D1 and D2.

Model results and shoreline change data for modeled Area A, seaward of Cape Canaveral, are illustrated in Figure 4-41 (Kelley et al., 2001). Analyses indicate that the shoreline was stable about 6 km south of Port Canaveral. Shoreline change results showed net accretion from the Cape south to Port Canaveral for all time periods (see Section 3.0).

This trend was not replicated for modeled transport gradients, which showed an area of high accretion at the Cape followed by an area of significant erosion between the Cape and Port Canaveral. The model had difficulty predicting transport rates in this area due to complex offshore bathymetric features associated with Canaveral Shoals and limitations related to wave modeling under diffracting conditions. Furthermore, STWAVE propagates wave energy within a ±90 degree sector from the cross-shore axis of the grid, which is important in areas where the shoreline angle is steep relative to the axis of the grid (e.g., just south of Cape Canaveral).

Based on shoreline curvature north of Port Canaveral, significant erosion was predicted immediately south of the cusp of Cape Canaveral (as indicated by the modeled gradient of transport potential). However, historical shoreline change data indicated substantial accretion in this area. The primary reason for this accretion likely was due to the shoal serving as a sediment source for beaches to the south. This cross-shore transport mechanism was not considered in longshore sediment transport predictions. For shorelines where nearshore shoals exhibit significant diffraction and potentially serve as a sediment source to the beach system, modeled sediment transport potential may not match observed trends in shoreline change. South of Port Canaveral, away from the influence of Cape topographic and bathymetric features, trends predicted by the sediment transport potential model match well with historical shoreline change.

For Area B, long-term shoreline change data covering the periods 1877 to 1970 were used to quantify trends (see Section 3.0). An additional analysis of short-term (1972 to 1993) shoreline change trends was completed using beach profile data available from the FDEP. Short-term analysis was performed to provide an estimate of shoreline change for a period of time similar to that covered by the WIS wave dataset. Methods used for compiling and analyzing historical data sets are described in Section 3.0. Alongshore variations in sand transport were determined using computed values of transport potential for modeled existing conditions for each shoreline.

Modeled sand transport gradients for Area B generally agreed with trends in shoreline change (Figure 4-42). Long-term (1877 to 1970) shoreline change rates illustrated that this area was generally stable, with less than 0.5 m/yr changes in shoreline position in most areas. Change rates were greatest in the vicinity of Sebastian Inlet (N 3081900). Short-term (1972 to 1993) shoreline change rates exhibited greater variability, but the trend documented a fairly stable to slightly erosional shoreline. The computed gradient in sediment transport potential indicated fairly stable conditions, with no major accretional or erosional hot spots. Minor differences between the two results exist near Sebastian Inlet. However, the computational method for determining gradients in transport was not expected to calibrate well in areas where jetties or groins exist. Overall, good agreement existed between observed shoreline change and longshore gradient in modeled transport potential.

For modeled Area C, long-term and short-term shoreline change rates indicated that the modeled area was stable to erosional, with change rates generally less than 0.5 m/yr (Figure 4-43). The computed gradient in sediment transport potential illustrated small variations along the shoreline landward of Borrow Sites C1 north and C1 south (Figure 4-43), consistent with low shoreline change rates in Area C.

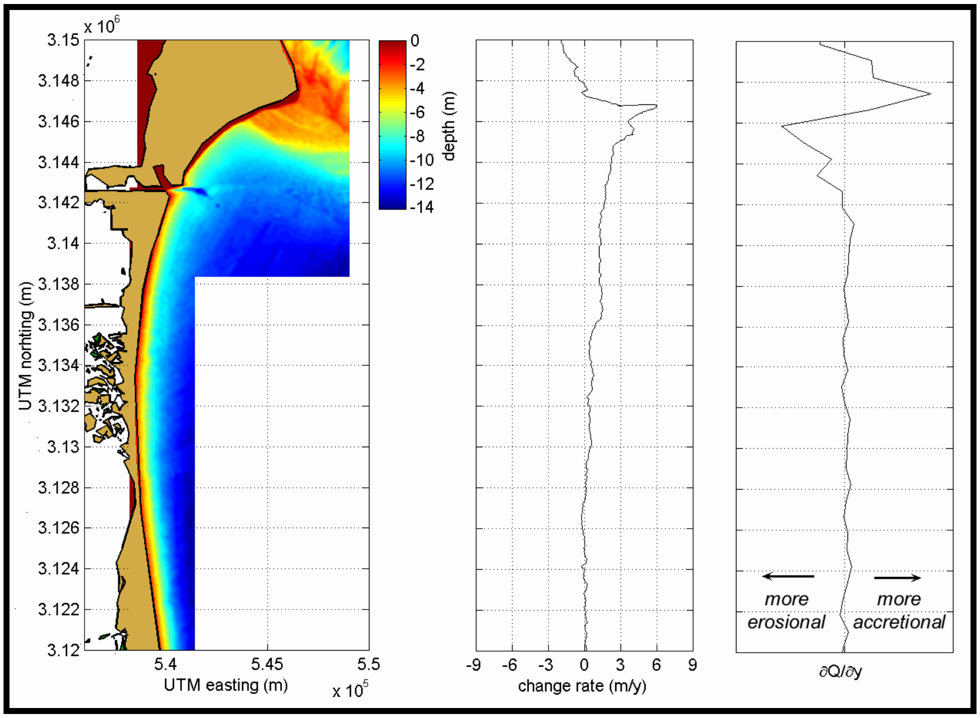

Figure 4-41. Historical shoreline change and gradient of modeled transport potential (dQ/dy) for the shoreline landward and south of Area A1. The gradient in transport potential was determined using the total net transport computed using 20 years of WIS data.

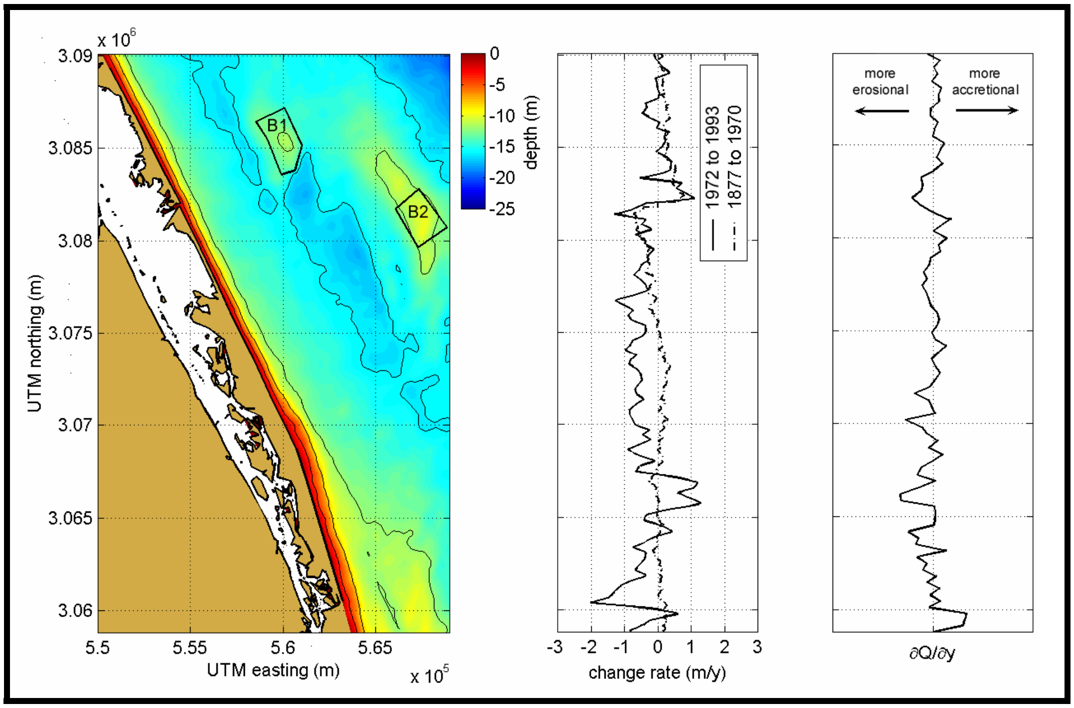

Figure 4-42. Historical shoreline change and gradient in modeled transport potential (dQ/dy) for the shoreline of Area B. The middle plot shows shoreline change for two time periods: 1877 to 1970 (black dash-dot line) and 1972 to 1993 (black solid line). The gradient in transport potential was determined using the total net transport computed using 20 years of WIS data.

For Area D (Jupiter Inlet), long-term (1887 to 1970) shoreline change rates indicated that the shoreline was stable, with change rates less than 0.5 m/yr (Figure 4-44). Short-term rates for this area illustrated much greater variation, primarily due to extensive beach nourishment projects that have been placed along this shoreline, including a 2.7 mcm project begun in 1973 for the shoreline north of the "S" curve. Because beach nourishment was included in the shoreline data, a comparison with the modeled gradient in sediment transport is less certain than with previous examples. The gradient in transport potential illustrated an area of high erosion potential located near N 2,987,200. The point of maximum negative gradient corresponds to the location of the "S" curve along the shoreline. This hot spot is not observed in either estimate of shoreline change for this area.

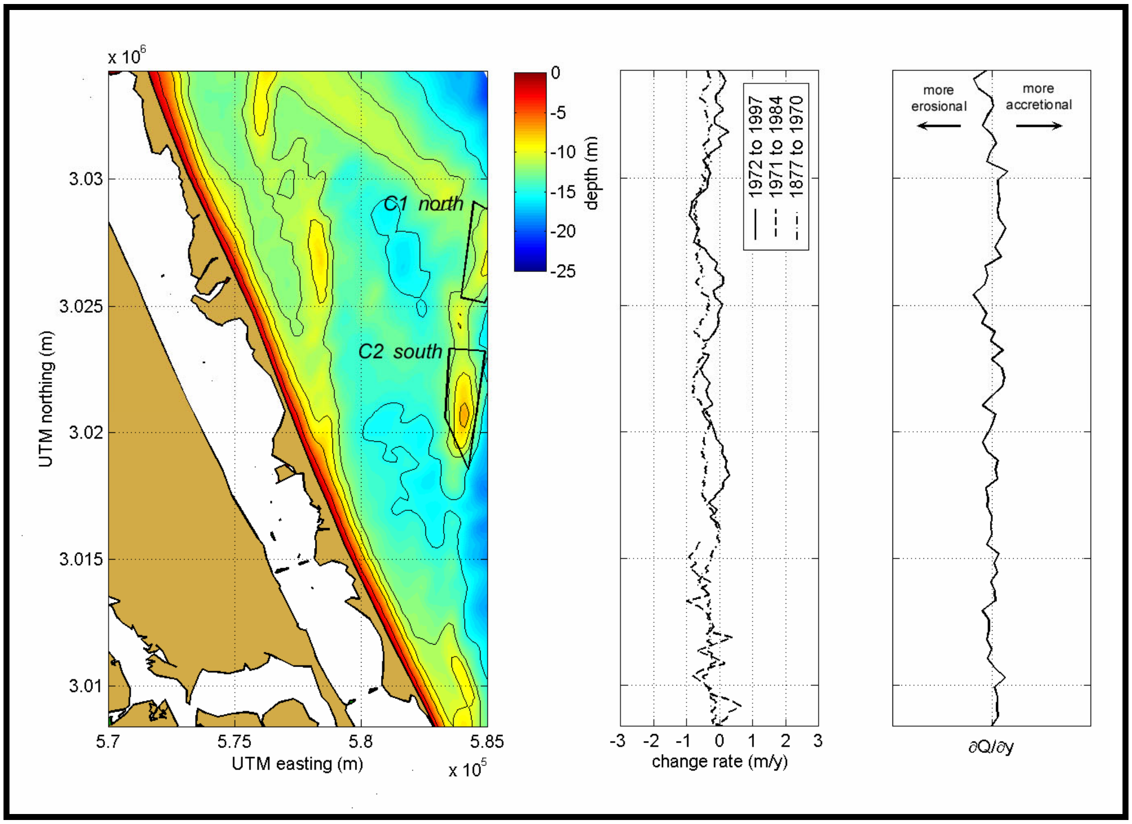

Figure 4-43. Historical shoreline change and gradient in modeled transport potential (dQ/dy) for the shoreline of Area C. The middle plot shows shoreline change for two time periods: 1877 to 1970 (black dash-dot line), 1972 to 1997 for St. Lucie County (black solid line), and 1971 to 1984 for Martin County (black dash line). The gradient in transport potential was determined using the total net transport computed using 20 years of WIS data.

4.2.2.2 Significance of Proposed Dredging

The significance of changes to longshore transport along the modeled shoreline resulting from dredging proposed borrow sites to their maximum design depths was determined using the method described in Kelley et al. (2004). For each modeled area, dredging impact significance was determined using several wave model runs in addition to the runs executed to determine the magnitude of borrow site impacts from existing to post-dredging conditions. Twenty 1-year periods were run for each area using the same directional binning as existing and post-dredging runs. Sediment transport potential was computed for each 1-year period. The standard deviation of transport potential then was computed at each grid node, providing an estimate of annual variability in sediment transport potential along the shoreline. As such, this method incorporated the temporal and spatial variability of transport potential along the modeled shoreline. The criterion for determining dredging significance was one-half of a standard deviation (±0.5σ). For modeled borrow site impacts that exceed this limit, the borrow site would be rejected as designed.

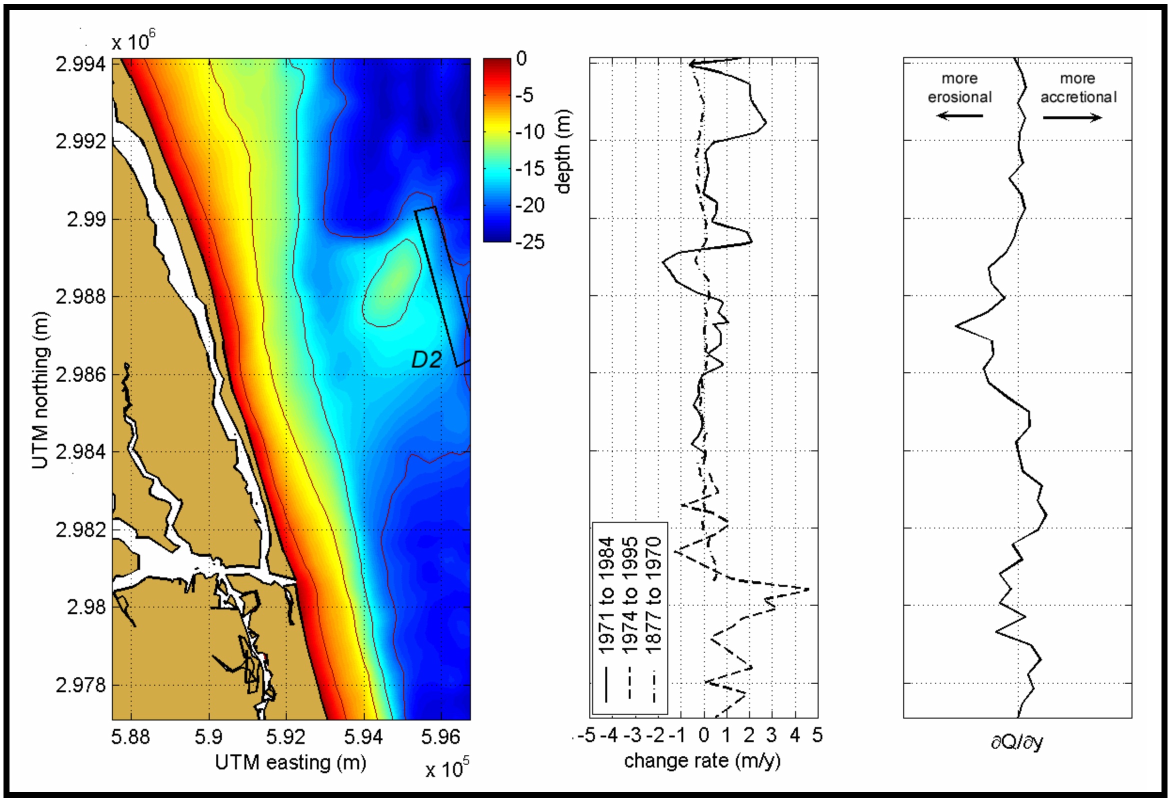

Figure 4-44. Historical shoreline change and gradient in modeled transport potential (dQ/dy) for the shoreline of Area D (near Jupiter Inlet). The middle plot shows shoreline change for two time periods: 1877 to 1970 (black dash-dot line), 1972 to 1997 for Martin County (black solid line), and 1971 to 1984 for Palm Beach County (black dash line). The gradient in transport potential was determined using the total net transport computed using 20 years of WIS data.

Model output for the region south of Cape Canaveral indicated that the significance envelope was approximately 20% of the mean computed net transport potential in the area of greatest impact from the borrow site in Area A1 (Figure 4-45). The maximum modeled decrease in south-directed transport for post-dredging conditions was about a 40,000 m^3/yr, just south of Port Canaveral. The modeled sand excavation volume of 13.6 mcm was considerably greater than the estimated 3.4 mcm for present beach nourishment requirements in Brevard County (USACE, 1999a). Although the modeled difference was within the transport significance envelope, the magnitude of impact resulting from cumulative dredging extraction at this site may require further analysis to ensure that no detrimental impacts occur.

Due to the influence of Cape Canaveral and the series of migrating ridges and troughs on Canaveral Shoals, a direct relationship between observed shoreline change and the modeled longshore gradient in sediment transport potential could not be established. Therefore, the utility of comparing changes in sediment transport potential associated with sand mining to natural variability in longshore sediment transport may have limited applicability in this region.

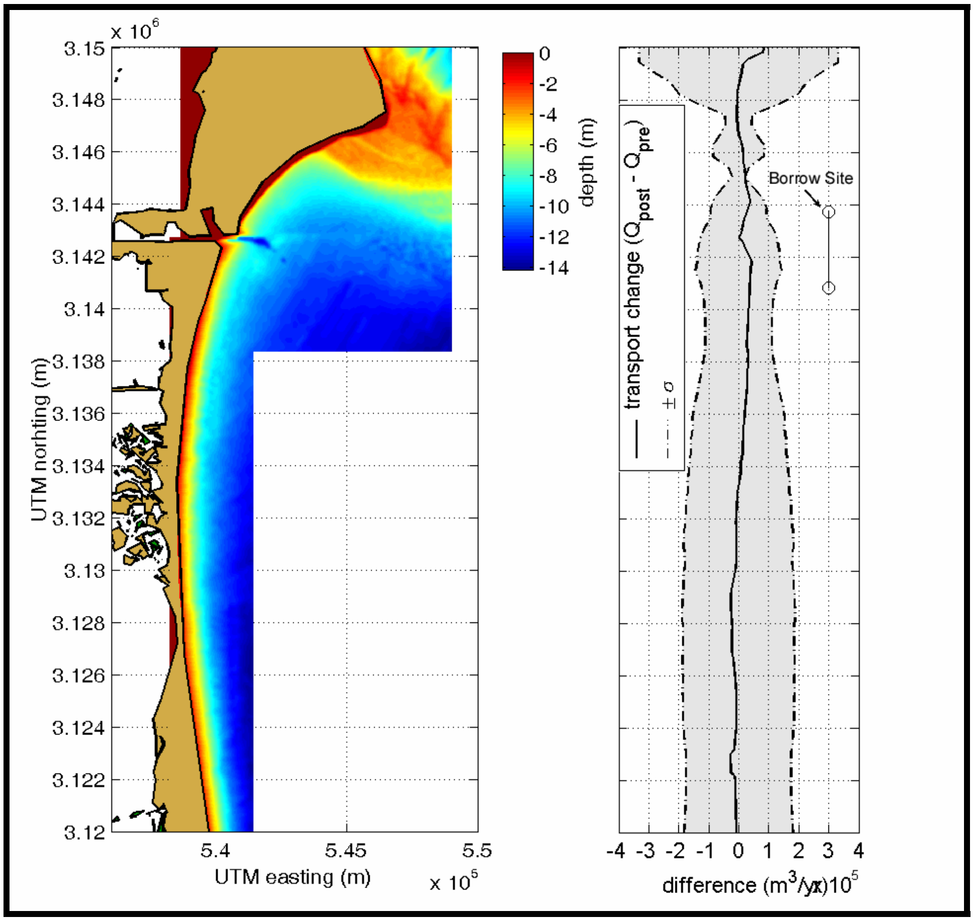

Figure 4-45. Transport potential difference between existing and post-dredging conditions, with transport significance envelope for the shoreline landward and south of the borrow site in Area A1. Negative change indicates that the post-dredging transport potential is more southerly than the computed existing transport potential.

This is most clearly illustrated by the change in transport rates at the northern limit of the model grid, where a decrease in south-directed transport of 80,000 m^3/yr is predicted. Because STWAVE does not explicitly include the influence of wave diffraction, modeled transport rates in regions influenced by diffraction may not be reasonable. For cases where wave diffraction is a dominant component of wave propagation through a borrow site and to the shoreline, a spectral wave model that explicitly incorporates the influence of wave diffraction may be more beneficial for predicting potential impacts of borrow site excavation. For Brevard County, the region influenced by wave diffraction was north of Port Canaveral.

For the Area B borrow sites, the ±0.5σ significance envelope was at a nearly consistent level of ±100,000 m^3/yr (Figure 4-46). The impacts that result from dredging

Borrow Sites B1 and B2 occur within this envelope, indicating that these sites would not produce significant modifications to coastal processes along the shoreline. Dredging impacts were computed by subtracting the transport potential curve computed for existing conditions from the transport potential computed for post-dredging conditions. The largest calculated differences between existing and post-dredging transport potential occurred north of Sebastian Inlet (where the transport rate becomes more southerly by 30,000 m^3/yr) and just south of the inlet (where transport rates become less southerly by 30,000 m^3/yr).

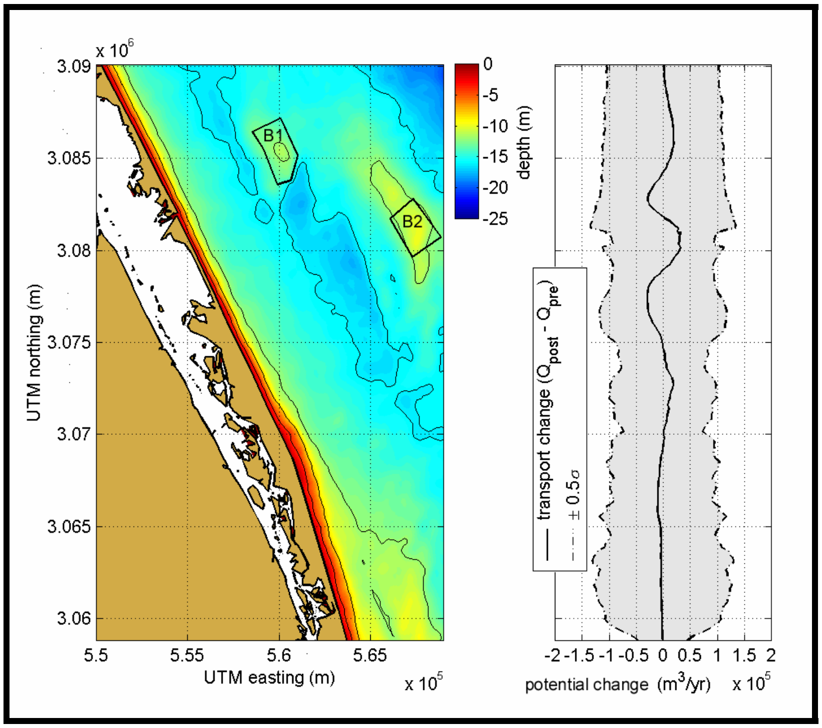

Figure 4-46. Transport potential difference between existing and post-dredging conditions, including the natural transport variability envelope for Area B borrow sites. Negative (positive) change indicates that the post-dredging transport potential is more southerly (northerly) than the computed existing conditions transport potential.

For Borrow Sites C1 north and C1 south, the ±0.5σ significance envelope computed for this area ranged from approximately ±100,000 m^3/yr at the northern limit of the area to ±50,000 m^3/yr at the southern limit (Figure 4-47). The potential impacts from dredging Sites C1 north and C1 south to the depths shown in Table 4-6 indicated that the significance envelope was exceeded along a 2-km length of shoreline approximately 18 km north of St. Lucie Inlet. At the point of maximum dredging-induced change along the shoreline, the significance level was ±60,000 m^3/yr, and the computed change in transport potential was 85,000 m^3/yr. As designed, this borrow site configuration may not be acceptable. If a borrow site redesign were required, the most likely change would be a reduction in maximum dredging depth to reduce site impacts.

The envelope of significant change in transport rates under natural wave propagation conditions for Borrow Site D2 in Area D ranged from approximately ±50,000 m^3/yr in the north to ±100,000 m^3/yr in the south, with a maximum of approximately ±150,000 m^3/yr occurring south of the "S" curve (Figure 4-48). Modeled dredging impacts to transport potential for Site D2 were minimal; predicted changes were well within the transport variability significance envelope. Maximum dredging impacts to transport potential were approximately ±10,000 m^3/yr. The small impacts for this area (compared with previous modeled areas) resulted from larger borrow site depths, smaller excavation volume, and the sheltering effect of the shoal landward of D2.

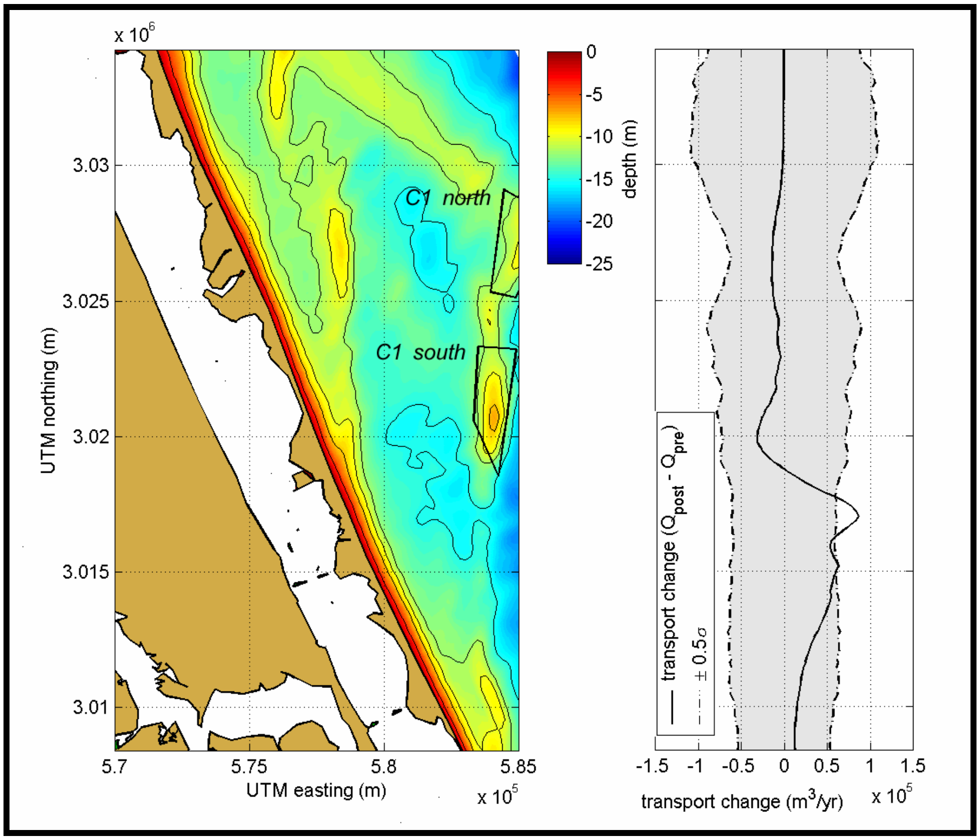

Figure 4-47. Transport potential difference between existing and post-dredging conditions, including the natural transport variability envelope for Area C borrow sites. Negative (positive) change indicates that the post-dredging transport potential is more southerly (northerly) than the computed existing conditions transport potential.

4.3 SUMMARY

This section documented results of wave modeling and sediment transport potential computations performed to assess the significance of impacts that may result from dredging sand at six proposed borrow sites offshore central east Florida. STWAVE simulated how wave fields were modified by bathymetry offshore Florida. Dominant wave conditions were developed using the 20-year WIS wave hindcast for stations offshore borrow sites in central east Florida. 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. Alongshore variations in the computed gradient of sand transport 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.

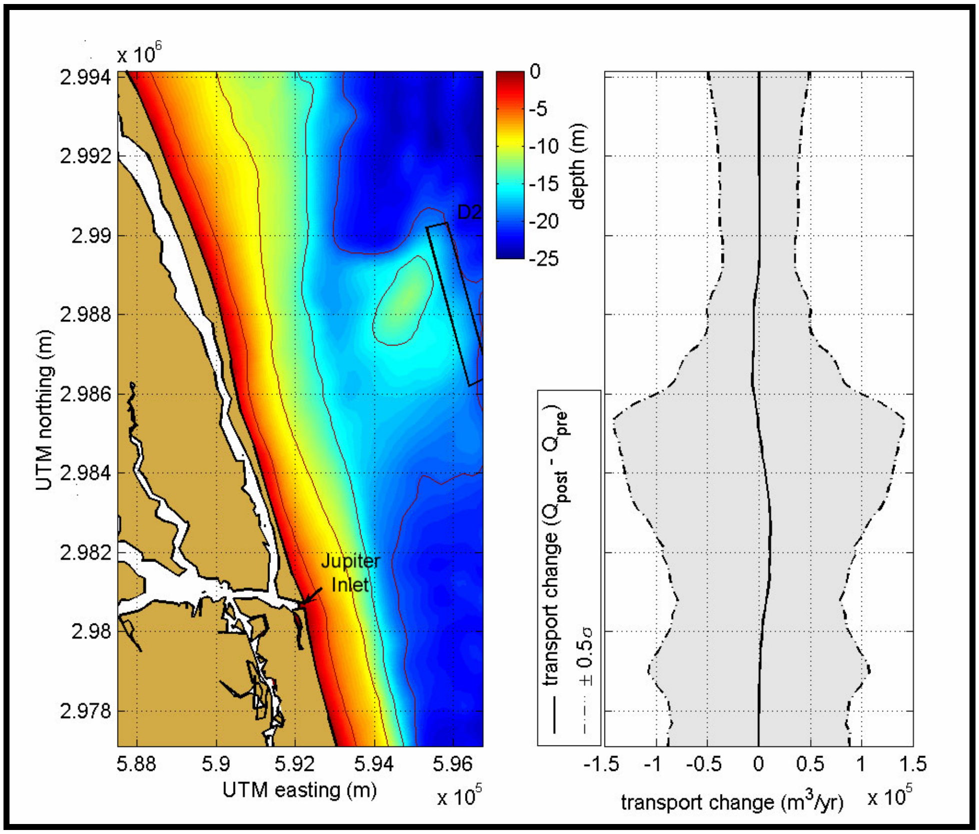

Figure 4-48. Transport potential difference between existing and post-dredging conditions, including the natural transport variability envelope for Borrow Site D2 in modeled Area D. Negative (positive) change indicates that the post-dredging transport potential is more southerly (northerly) than the computed existing conditions transport potential.

Once the change in sediment transport potential was determined for existing and post-dredging conditions, the significance of these changes was evaluated by applying a criterion developed by Kelley et al. (2004) based on the natural temporal and spatial variability of sediment transport along a modeled coastline. Each of the 20 years in the WIS record were modeled individually to determine the significance criterion envelope. The standard deviation of sediment transport potential then was computed for each modeled area. A determination of dredging significance was made by comparing predicted change in transport potential between existing and post-dredging conditions to a significance envelope of ±0.5 to 1σ in natural transport variability along the shoreline. It was determined that no significant changes in longshore sediment transport potential would result from modeled borrow site configurations for Areas A, B, and D. However, the proposed sites in Area C do have significant impacts to transport potential along the shoreline. Therefore, Area C sites should be redesigned so impacts occur within acceptable limits, most likely by reducing the maximum depth of excavation at the sites.

5.0 CIRCULATION AND OFFSHORE SEDIMENT TRANSPORT DYNAMICS

This section analyzes the physical processes regime of the central east Florida continental shelf and discusses circulation and sediment transport processes to evaluate the potential environmental impact of offshore sand mining. Current and wave processes provide physical mechanisms for moving sediment within the coastal zone of central east Florida. The following discussion documents current and shelf sediment transport processes potentially impacted by sand mining at specific offshore sand borrow sites.

5.1 CURRENTS AND CIRCULATION

Current measurements along the central east Florida shelf were acquired to develop an understanding of shelf circulation processes at proposed offshore borrow sites. These measurements included long-term current meter time series and synoptic spatial surveys at specific offshore shoals for approximately 24-hour periods. Long-term current meter measurements were obtained from previous research programs conducted in the study area. The synoptic observations were obtained specifically for this study and consisted of current profiling from survey vessels at Sand Resource Areas B1 and B2.

5.1.1 Historical Data Analysis

Long-term measurements of shelf currents were evaluated to develop an understanding of the time scales and magnitudes of circulation processes. Several data sets were used for this analysis. These data were obtained in two locations offshore St. Lucie Inlet at inner- and mid-shelf depths. Both data sets were obtained from Dr. Ned Smith of Harbor Branch Oceanographic Institution. There were few other sources of available current meter data for the study region.

Mid-shelf measurements were obtained in 44-m water depth; the sensor was positioned 2 m off the bottom. Data were obtained during two measurement periods: June to November 1977 (137-day record) and March to July 1978 (also 137-day record). A 115-day gap during winter months existed between measurement phases. Data were received as 2-hour averages. Inner shelf measurements, obtained in 10-m water depth near the sea buoy at St. Lucie Inlet, represented current conditions from August to September 1991. Data were received as 20-minute samples, each sample resulting from a 10-minute average at the beginning of the sample window.

Data analyses included statistical sampling, time series analysis including spectral estimates, digital filtering, and tidal harmonic analysis. The analysis goal was to determine significant time scales and amplitudes of observed current variability at potential offshore borrow sites.

5.1.1.1 Description of Observed Currents

Currents were presented as along-shelf and cross-shelf components for the mid-depth station (Figure 5-1). A comparison of these two data sets shows along-shelf currents generally were more variable and stronger than cross-shelf currents. Cross-shelf amplitudes were about ±20 cm/sec, while along-shelf variations approached 50 cm/sec at times. Along-shelf flows were dominated by periodic events (pulses) that persisted for several days. These events were characterized by strong up-shelf (to the north) or down-shelf (to the south) currents. Down-shelf events were observed in October-November 1977 and March-April 1978. Up-shelf events were more common in summer months.

Current observations obtained on the inner shelf near St. Lucie Inlet during late summer 1991 demonstrated similar variability; along-shelf currents were more variable than cross-shelf currents (Figure 5-2). Peak currents approached 50 cm/sec to the north, with sharp flow reversals over time scales of about 1 day. Tidal flow from St. Lucie Inlet may have influenced these data.

The along-shelf dependence of current observations is illustrated in Figure 5-3. The shoreline is oriented approximately north-northwest to south-southeast (340°/160°) at St. Lucie Inlet, and the rose diagrams show a dominance of flow parallel to the coast. While some occurrences of predominantly cross-shelf flow were observed, cross-shelf currents were generally quite weak. Along-shelf currents were most common.

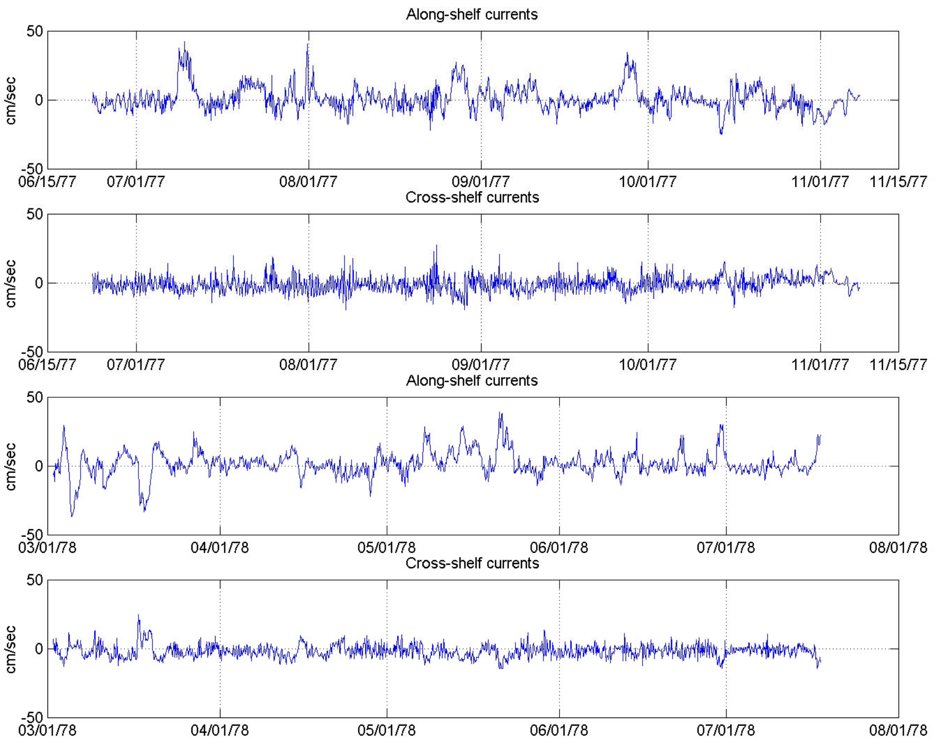

Figure 5-1. Time series of mid-shelf current observations offshore St. Lucie Inlet. Top two plots represent along-shelf and cross-shelf components of near-bottom currents in 44-m water depth obtained June through November 1977. Bottom two plots represent the time period March through July 1978. Data courtesy of Dr. Ned Smith, Harbor Branch Oceanographic Institution.

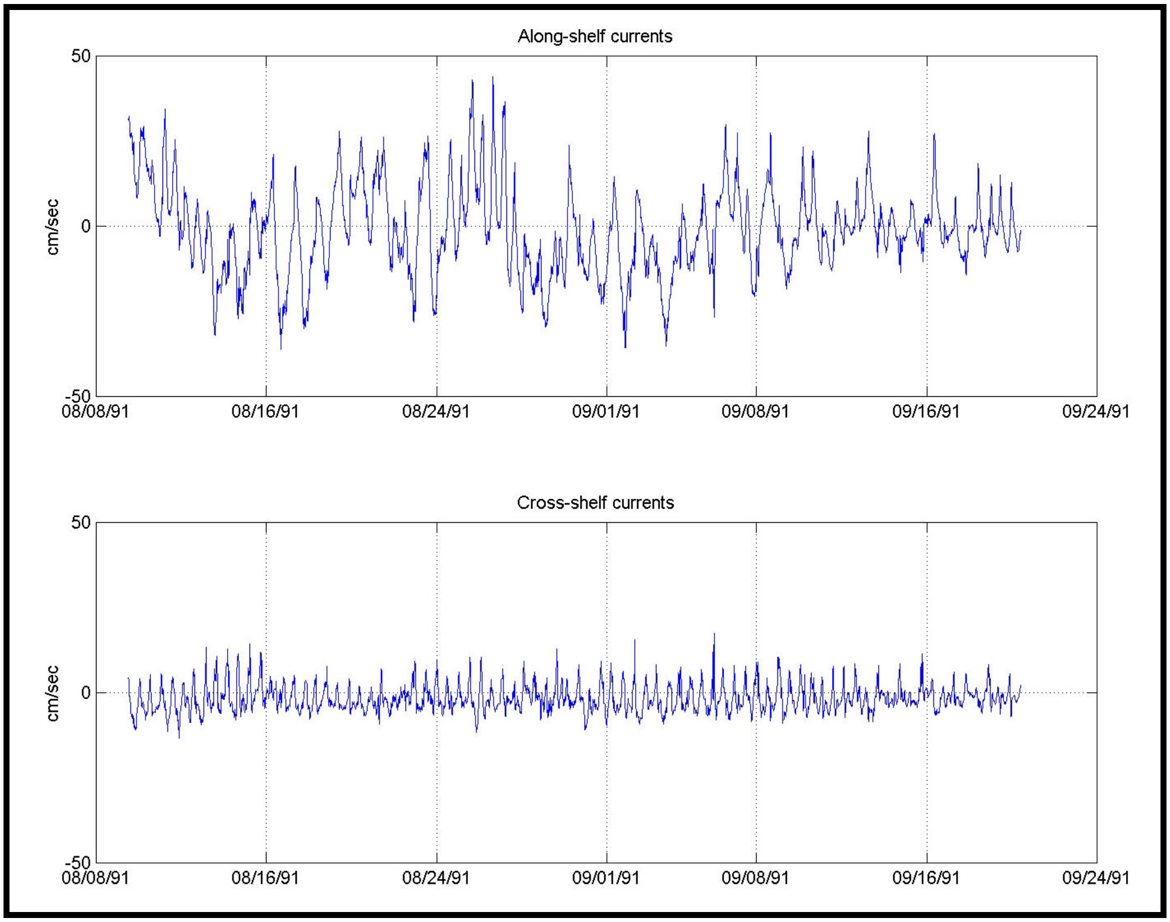

Figure 5-2. Inner shelf current meter observations obtained near St. Lucie Inlet, August 9 to September 20, 1991. Top plot represents the along-shelf current component; bottom plot represents the cross-shelf component. Data courtesy of Dr. Ned Smith, Harbor Branch Oceanographic Institution.

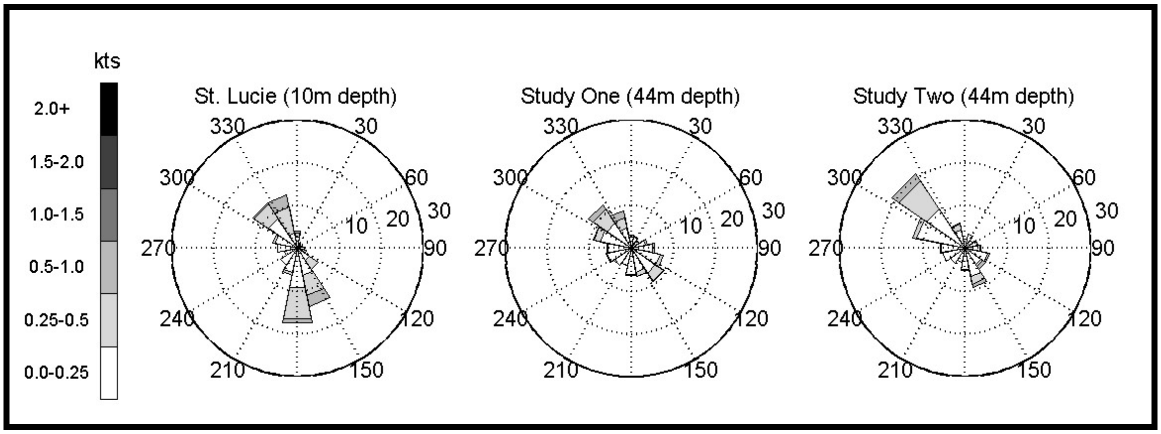

Figure 5-3. Summary of current meter observations presented in Figures 5-1 and 5-2. These graphical presentations show the dominance of along-shelf flow.

Table 5-1 presents summary statistics for the current meter data sets. The magnitude of maximum currents (i.e., positive or northward currents) were always greater than the magnitude of down-shelf currents (i.e., negative or southward currents). Mean along-shelf flows were slightly positive but near zero due to up- and down-shelf current reversals. Mean cross-shelf currents were negative (i.e., onshore). Peak bottom currents of 42 cm/sec were measured on the mid-shelf; these currents were directed northerly (331 deg). Peak current speeds of 44 cm/sec were observed on the inner shelf, oriented toward 340 deg.

Table 5-1. Statistics of current observations.

Location	Along-Shelf Component (cm/sec)				Cross-Shelf Component (cm/sec)			
	Mean	Max	Min	Variance	Mean	Max	Min	Variance
Mid-shelf (44 m) (Jun-Nov 1977)	1.2	42.2	-25.1	77.7	-0.7	27.4	-19.4	29.8
Mid-shelf (44 m) (Mar-July 1978)	1.8	39.2	-36.7	80.8	-1.6	25.1	-14.5	21.9
Inner shelf (10 m) St. Lucie Inlet	-1.1	44.0	-36.2	164.4	-1.6	17.4	-13.3	15.2

Variance of the along-shelf component was about 3 to 4 times greater than the cross-shelf component at the mid-shelf site. On the inner shelf, the along-shelf energy was an order of magnitude greater than cross-shelf energy. Relatively greater energy parallel to the shoreline in the inner shelf data set may result from several factors, including the presence of a tidal inlet, the relatively short record may have coincided with an unusually active time period, and nearshore regions may be more energetic than deeper areas further offshore.

Numerical analyses of these data sets showed energy concentrated at particular spectral bands. Spectral density estimates were derived for these data sets and presented as variance-preserving spectra (Figure 5-4). Largest areas beneath the curves represented the greatest spectral energy content. Most energy was in the along-shelf component in the band 0.1 to 0.5 cycles per day or periods about 2 to 10 days. There were sharp peaks at the diurnal and semi-diurnal bands, representing the principal tides, but these contained little of the overall energy, as tidal peaks were quite thin relative to lower-frequency bands. There was significant cross-shelf energy in the semi-diurnal band from June to November, less semi-diurnal energy from March to July. Subtidal energy in the cross-shelf direction was weak. Most current energy at the mid-shelf location was contained in along-shelf subtidal frequency bands.

5.1.1.2 Current Components

Harmonic analysis of the data sets removed selected tidal constituents from the records, isolating the residual, or non-tidal currents. Calculation of variance for these tidal constituents revealed that tides at the mid-shelf location were weak, accounting for about 5% of the overall current energy. The residual signal dominated mid-shelf observations. Peak tidal speeds at mid-shelf were about 5 cm/sec; tidal ellipses were parallel to the bathymetry but eccentricity was low (more circular). Tides on the inner shelf near St. Lucie Inlet accounted for 30% of the overall current variance. Inner shelf tidal variance was greater in the along-shelf component than the cross-shelf component; scatter plots of tidal currents show ellipses oriented parallel to the shoreline. Peak tidal current speeds near St. Lucie Inlet approached 20 cm/sec.

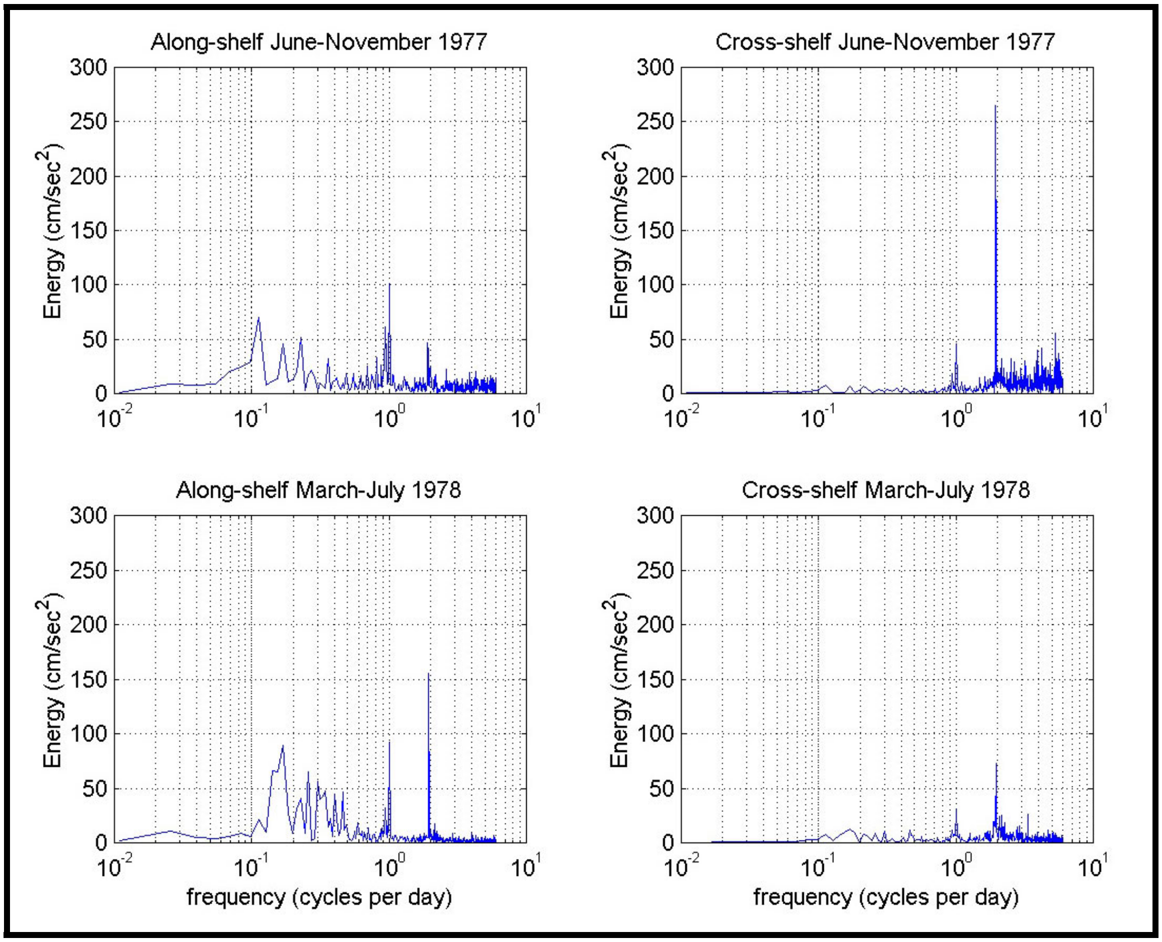

Figure 5-4. Variance-preserving spectra for mid-shelf current meter observations presented in Figure 5-1. Subtidal processes (frequencies less than 1 cycle per day) contained most of the current energy; along-shelf energy was 3 to 4 times greater than cross-shelf energy.

The residual signal represented current motions due to non-tidal processes. These signals were reduced further with a 33-hour low-pass filter to remove high frequency noise. The remaining subtidal signal represented current processes at lower frequencies, currents shown to contain significant spectral energy (Figure 5-4). These currents were found to possess more than half of the total current energy at the inner shelf location and between 60% and 75% of the total energy at the mid-shelf location. Subtidal processes were responsible for the periodic high-speed events observed in the original time series (Figures 5-1 and 5-2).

Two primary forcing influences, winds and Florida Current eddy effects, were investigated as potential causes for subtidal energy. Correlation between wind stress near St. Lucie Inlet and currents at the mid-shelf location accounted for about 10% of the along-shelf subtidal variance predicted by along-shelf wind stress. Correlation improved when along-shelf winds were compared with cross-shelf flow; about 18% of the cross-shelf variance could be predicted by wind stress. Correlations were better for the March to July data set than for the June to November data set. About 1% of the cross-shelf and along-shelf variance was explained by cross-shelf wind stress. The higher correlation between cross-shelf currents and along-shelf wind stress may be due to Ekman dynamics; a northward wind stress may cause currents in the surface layer to veer slightly to the right of the wind direction or offshore. Bottom currents then would be drawn shoreward (or to the left) to balance the induced pressure deficit (Pickard and Emery, 1990).

On the inner shelf near St. Lucie Inlet, subtidal currents generally moved in the direction of wind stress. About 26% of the along-shelf current variance was predicted by along-shelf winds, and about 10% of the cross-shelf current variance was due to winds.

According to the literature, most current energy on the southeast Florida shelf can be attributed to meanders or spin-off eddies generated from the Florida Current (see Section 2.2). These perturbations of the Florida Current propagate northward along the Florida shelf as wave-like filaments or counter-clockwise rotating eddies. These processes have great influence on the outer shelf where water depths are greater than about 75 m, with their influence diminishing into shallow water on the inner shelf. Eddies have time scales of approximately 2 to 14 days, depending on location and time of year (Lee, 1975; Lee and Mayer, 1977; Lee and Mooers, 1977; Santos, et al., 1990). Spin-off eddies transport subtropical water from the Florida Current onto the shelf (Lee and Mayer, 1977), and also induce onshore upwelling of deeper, cooler water (Zantopp et al., 1987). The result can be sharp temperature gradients surrounding the eddy.

Comparison of subtidal current variability with temperature variability at the mid-depth site yielded mixed results between the two time periods. From June to November 1977, 21% of the cross-shelf current variability and 8% of the along-shelf current variability could be predicted by temperature changes. However, from March to July 1978, these percentages fell to about 2%, suggesting most subtidal variability may be due to indirect response to meanders, spin-off eddies, or other manifestations of the Florida Current.

5.1.2 Field Data Collection

Field measurements of currents over Thomas Shoal and within Areas B1 and B2 were conducted Fall 2000, Spring 2001, and Fall 2001. The purpose of these measurements was to observe spatial and temporal flow variability over a shoal typical of a potential sand resource area in central east Florida. Results of the surveys yielded observations on flow variations in a localized region and were used in concert with long-term historical current data to augment our understanding of flow characteristics on the inner-continental shelf off central east Florida. Observations support the results of historical data analyses, suggesting flow offshore central east Florida was dependent on local variations in wind conditions, regional patterns of the Florida Current, and local bathymetry. Tidal effects seem to be minor in comparison with other forcing mechanisms.

This section briefly describes field data collection procedures, including instrumentation, survey techniques, and data processing. Furthermore, flow conditions observed at the survey site are discussed. Setup conditions determining flow characteristics (i.e., winds and tides) were different during fall and spring surveys. The following describes how flow in Areas B1 and B2 responded to different forcing conditions. All current measurement plots are presented in Appendix D.

5.1.2.1 Survey Instrumentation and Techniques

The surveys were designed to measure currents across a central portion of the study area during an approximate 24- to 48-hour period under fall and spring conditions. A pre-defined set of transect lines were traversed at regular time intervals intended to span two to four complete tidal cycles to evaluate the spatial and temporal variation in current structure in the study area (Figure 5-5).

The survey transect grid was composed of eight lines designed to approximate a square figure-8 pattern. The survey grid extended approximately 7.6 km in the along-shelf direction and 4 km in the cross-shelf direction (Figure 5-5). The center line of three parallel cross-shelf lines was located perpendicular to the axis of the shallowest region of the sand shoal. The vessel began surveying in the northeast corner of the grid and traveled southeast (along-shelf) to the intersection with the center line (Line 1). The vessel rotated to the west, and traveled southwest across the shoal (cross-shelf, Line 2). Line 3, from the center line to the southwestern corner of the survey grid, was traversed in a southeast direction (along-shelf).

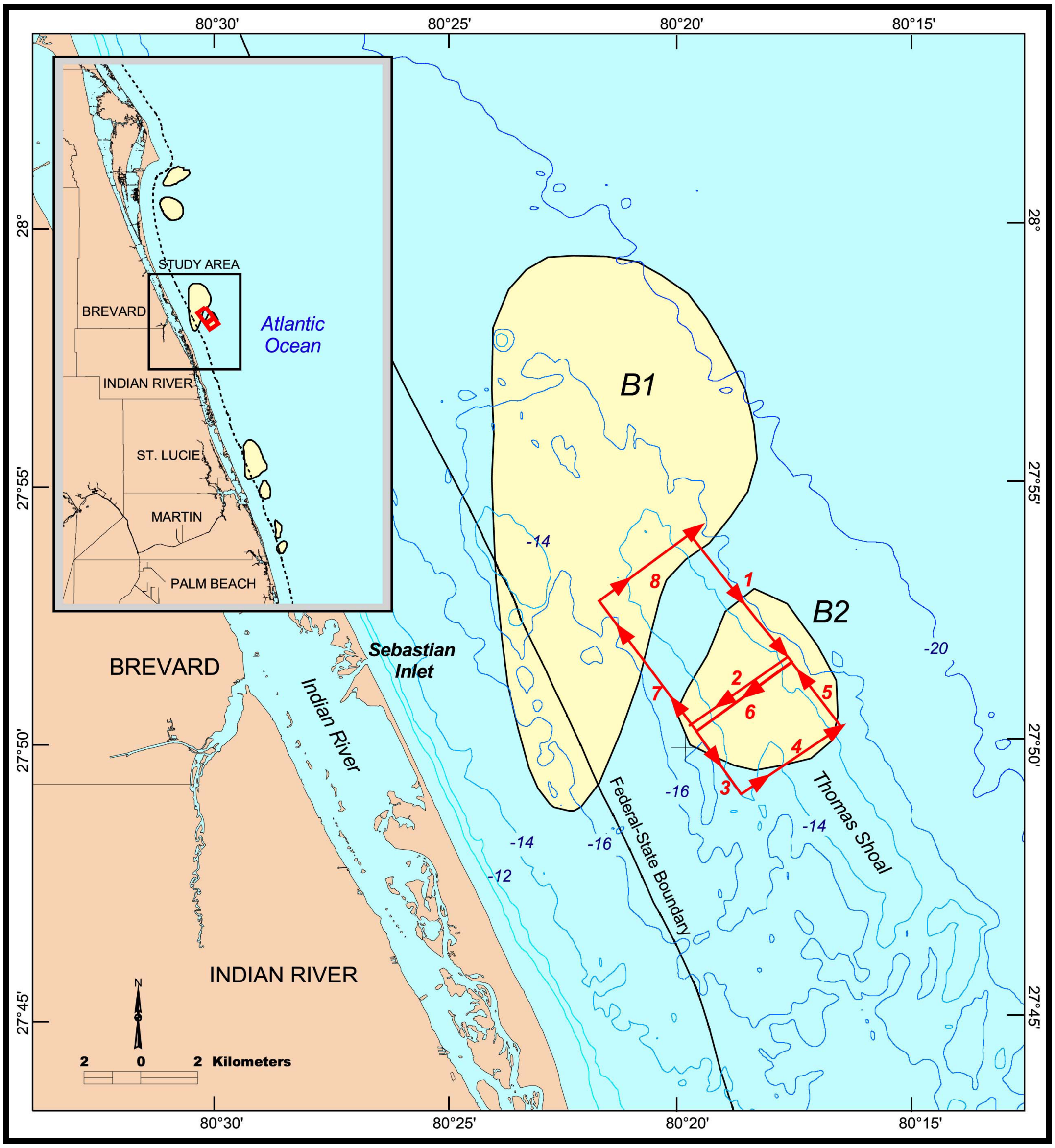

Figure 5-5. Bathymetric map of study area showing the ADCP survey line pattern displayed in red.

With the vessel on a northeast heading, the southern cross-shelf line was traversed to the southeastern corner of the grid (Line 4). Line 5 was run along-shelf, from the southeast corner of the grid to the intersection with the center line, and the center line was traversed a second time from northeast to southwest (Line 6). The vessel rotated to the north and proceeded in a northwest (up-shelf) direction traversing Line 7. Cross-shelf Line 8 closed the pattern, extending from the northwest corner of the grid to the northeast corner. Each line was completed in approximately 30 minutes, with an entire eight-line cycle traversed every 4 hours, surveying the centerline every 2 hours. This survey technique provided adequate spatial coverage of Areas B1 and B2, and it was designed with the cross-shelf bias to observe along-shelf flow, the more dominant process.

Each proposed survey would allow the completion of 12 cycles in a 48-hour period. Two cycles were completed during the Fall 2000 survey, and six cycles were completed during Spring and Fall 2001 surveys. The initial survey, September 19, 2000, was conducted aboard a 41-foot charter fishing boat, *Luna Sea*. The survey began at 0915 on September 19, but instrumentation problems delayed current measurement collection until 1645 hours. Although weather conditions in the morning on September 19 were favorable for surveying, wind speeds slowly increased throughout the day. At 1700 hours, wind gusts up to 7 m/sec were reported at the National Data Buoy Center (NDBC) station offshore Cape Canaveral. Winds blew out of the southeast causing large swell to propagate northwest along the axis of the survey grid. By 0500 on September 20, wind speeds reached 11 m/sec with gust up to 13 m/sec. The survey was terminated at 0322, September 20, when high speed, southeasterly directed winds made navigation of cross-shelf transect lines impossible. The September 2000 survey results showed pitch and roll of the boat was more variable than the instrumentation could resolve, resulting in a lack of confidence in current data measured under the given weather conditions.

The May 2001 survey was conducted aboard a 32-foot charter fishing vessel, *My Last Fling*. The survey began at 1947, May 29, and six cycles were completed before the survey was terminated at 2200 on May 30 due to unfavorable weather conditions. Details of this survey are discussed in Section 5.1.2.2. The fall survey was repeated in September 2001. Based on our experience and May 2001 survey results, a 24-hour current measurement survey was planned. At 1900 on September 4, 2001, the survey commenced aboard the Research Vessel *Barb-N-T*. Six survey cycles were traversed, concluding at 2000 on September 5; results are discussed in Section 5.1.2.3.

Currents were measured using an acoustic doppler current profiler (ADCP) mounted rigidly to a small vessel. The ADCP provided high-resolution measurements of the vertical structure of current flow beneath the instrument transducer. When mounted to a moving platform, such as a small vessel, and used to traverse regional areas, the result is a detailed synoptic view of the current field.

The ADCP was configured to balance maximum accuracy with reasonable vertical resolution, resulting in a standard deviation (or accuracy of current measurement) of approximately 1.3 cm/sec. Vertical resolution was 0.5 m or one velocity observation every 0.5 m water depth. Each vertical profile took approximately 4 sec to collect. Averaging parameters resulted in a horizontal resolution of approximately 10 to 12 m along a transect line.

Position information was collected using HYPACK®, an integrated navigation software package running on a personal computer, linked to a Trimble Pro XR differential GPS.

Position data were recorded in Universal Transverse Mercator (UTM) NAD83 coordinate system in meters. Position updates were available every 2 sec, although brief interruptions of position data were experienced when thunderstorms were in the area. These brief losses of position data (less than 10 sec) did not compromise results.

Surveys resulted in two types of data: current velocity profiles (or ensembles) and vessel position. ADCP data for a single transect consisted of velocity components at every depth bin for each profile. For these surveys, the two earth-referenced velocity components (V_{east} and V_{north}) were reported, as well as current speed, current direction, and error velocity. The conversion process outputs each ensemble profile as a function of depth (i.e., V_{east} versus depth, V_{north} versus depth, etc.). A series of ensemble profiles along transect line were recorded in each data file.

Time-stamped position data as northing and easting were recorded within HYPACK®. The ensemble profiles were merged with the position data to assign a unique x-y pair to every ensemble. This merging operation was done using time as the common link between HYPACK® and ADCP data files. By searching for the unique position at a specific time for each velocity profile, an accurate x-y location was assigned to each ensemble.

Current measurements are presented as vector maps throughout the survey areas. The vector maps represent vertically-averaged current velocities at specific locations within the survey domain. Velocity profiles were separated into near-surface, mid-depth, and near-bottom layers, with an average velocity value calculated for each depth layer. Vectors corresponding to a single survey cycle (8 transect lines) then were displayed on an area map. These vector maps were produced for the surface, mid-depth, and bottom layers for each of the six survey cycles. A series of plots shows temporal and spatial variation in horizontal and vertical currents during the survey. A complete set of vector maps for each survey is presented in Appendix D.

5.1.2.2 Spring 2001 Survey Results

Areas B1 and B2 were surveyed May 29 and 30, 2001. Thomas Shoal has a bathymetric relief of about 5 m that influences local circulation patterns approximately 5 km east of Sebastian Inlet (Figure 5-5). The shoal is crescent shaped with the major axis oriented northwest-southeast, approximately parallel to the orientation of the shoreline. The southern portion of the shoal extends towards shore, creating an onshore concavity.

Wind speed and direction were obtained for the survey period from an NDBC buoy 20 nm east of Cape Canaveral. In the days preceding the survey, winds were generally blowing from the south at 5 to 10 m/sec (Figure 5-6). Winds shifted north-northeast 5 days before the survey.

These northerly winds reached a maximum of 8 m/sec and then abated. On May 26, winds rotated south in a clockwise direction, reaching a maximum of almost 12 m/sec. On May 29 and 30, strongest winds blew out of the south-southwest, starting at 4 m/sec and increasing to as much as 8 m/sec. From 0100 to 1200 hours on May 30, winds shifted to the west-northwest decreasing in speed from 4 to 1 m/sec. Afternoon winds were southeast to east, reaching speeds of 6 m/sec. Field notes taken during the survey document increasing winds and waves leading up to a storm that passed through the area terminating the survey in the evening of May 30.

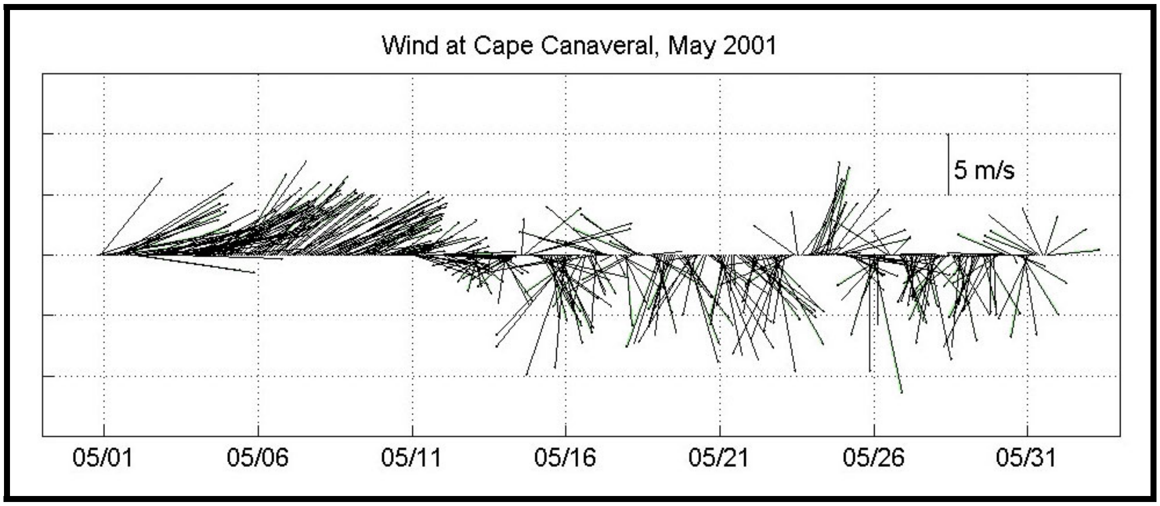

Figure 5-6. Wind conditions prior to and during the May ADCP survey measured at the NDBC buoy 20 nm east of Cape Canaveral.

Tidal elevations during the survey were collected from a NOS tide gage at the Trident Pier in Port Canaveral. Semi-diurnal tides dominate the region, specifically the M2 and S2 tidal constituents, resulting in two highs and two lows each day (Figure 5-7). On May 29, the survey began at 2035, coincident with the second low tide of the day. The survey ended on May 30 at approximately 2200 hours, 2 hours after the evening low tide, spanning two complete tidal cycles. The maximum tide range was 1.1 m.

Currents during the May survey were dominated by an underlying mean northward flow that was modified on the surface by winds and steered by bathymetry near-bottom (Figure 5-8). On the perimeter of the shoal, surface current speeds of 10 to 25 cm/sec correlated well with wind direction; winds out of the southwest drive a northerly flow. Across the shallowest portion of the shoal, surface flow was deflected onshore by local bathymetry. Near-bottom currents with speeds of 5 to 20 cm/sec typically flow up-shelf parallel to bathymetric contours. Cycle 1 current measurements suggest Ekman transport; surface currents veer right of wind direction (offshore), and bottom currents are drawn shoreward in response to a northward wind stress (Pickard and Emery, 1990). Ekman transport off the southeast coast of Florida is explained more thoroughly in Section 2.2. The circulation pattern described is illustrated in Figure 5-8 by the northeast surface current and the northwest bottom along Line 1. Ekman transport creates potential for upwelling, which persists into Cycle 2 but with less force due to a shift in wind direction.

Horizontal variability of currents measured mid-way through the May survey (Cycles 3 and 4) are not thoroughly explained by direct wind-forcing. As the wind shifted west-northwest, surface currents on the eastern side of the shoal flowed strongly to the east, while the mean underlying northward flow of bottom currents was impeded (Figure 5-9). On the western side and across the center of the shoal, surface and near-bottom current speeds were reduced. As wind speeds decreased (Cycle 4), surface currents slowed, but northerly-flowing near-bottom currents increased in energy (Figure 5-10). This underlying northerly mean flow, most clearly observed in near-bottom currents, was likely an indirect effect of the Florida Current. As discussed in Section 2.2, the frontal zone of the Florida Current meanders along the shelf break (approximately 40-m isobath). However, spin-off eddies along the western edge of the Florida Current have induced flow along the middle

(20- to 40-m isobaths) and inner shelf (shore to 20-m isobath). In winter and spring months, eddies propagate northward in response to southerly winds (Lee and Mayer, 1977). Florida Current eddies typically scale 10 km in the cross-shelf and 20 to 30 km along the shelf, forming every 2 days to 2 weeks, and historically have accounted for current variability that is poorly correlated with wind stress. During survey Cycles 4 and 5, decreasing speeds of surface currents correlated with decreasing wind speeds, but increased speeds of northerly bottom currents could not be explained by wind or tidal conditions. However, attributing these effects to the Florida Current is a bit speculative because the spatial and temporal scales of this survey are not adequate to resolve Florida Current effects.

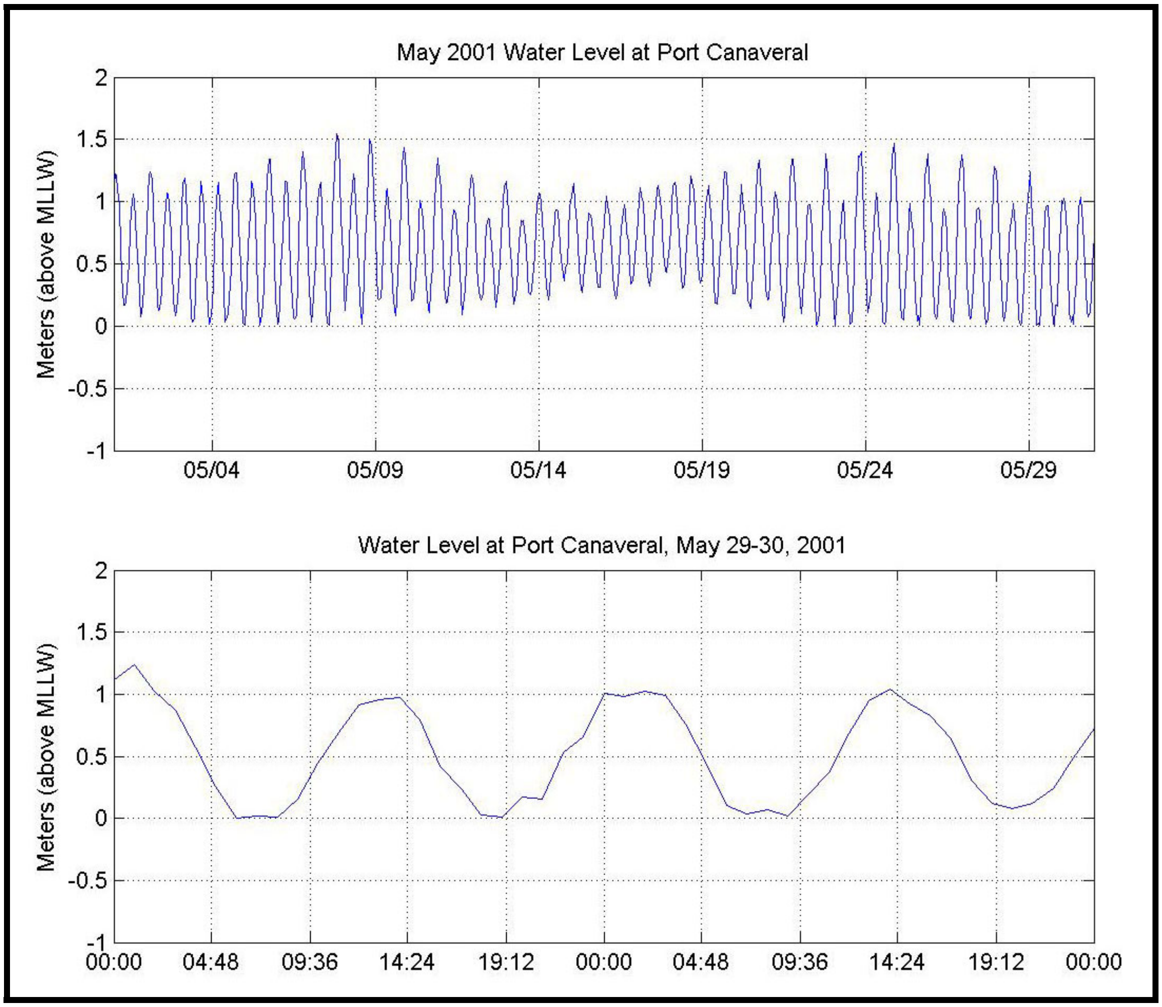

Figure 5-7. May 2001 water elevation measured at the NOS tide gage on the Trident Pier at Port Canaveral; the lower plot illustrates water level during the survey.

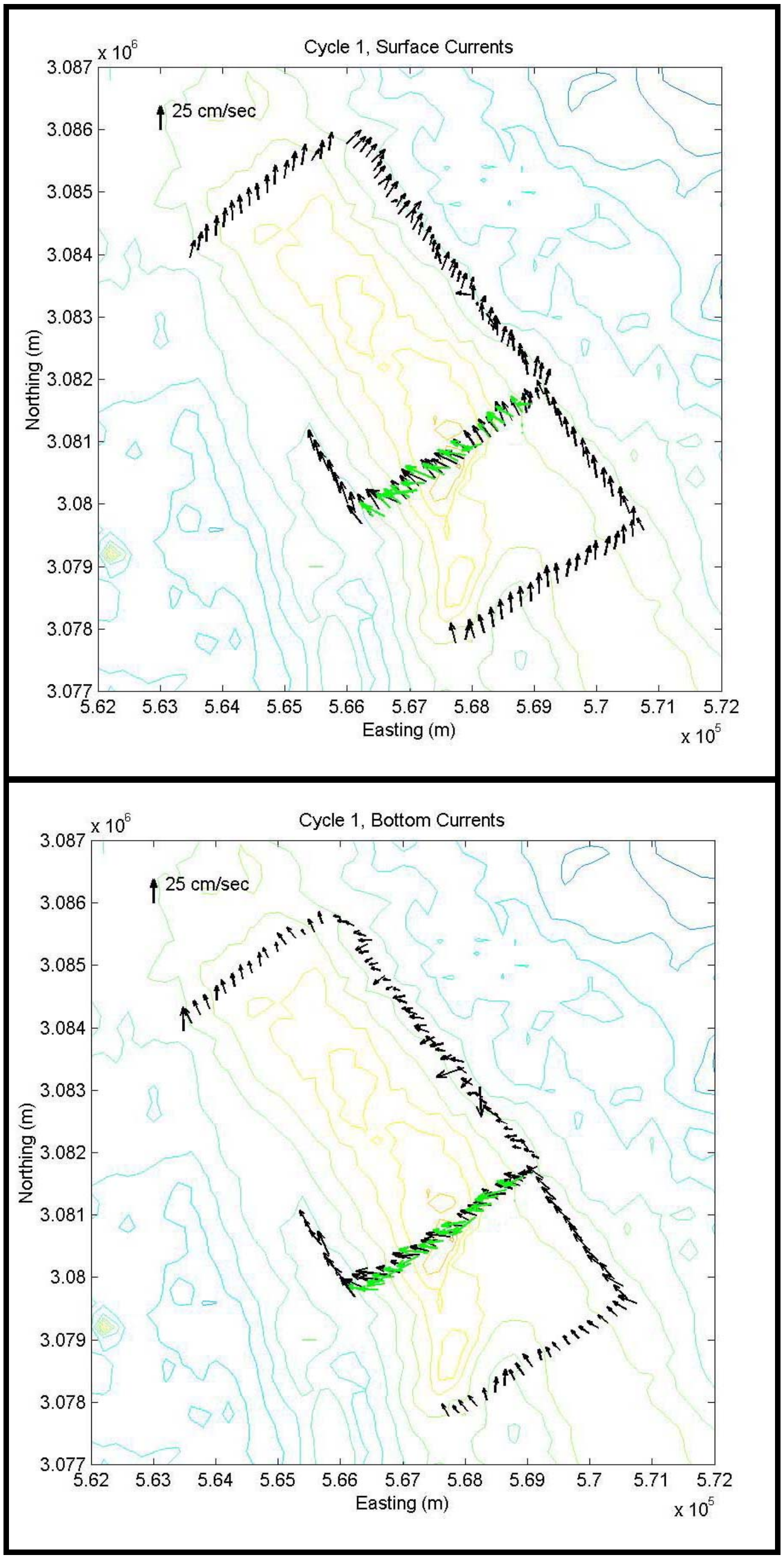

Figure 5-8. Cycle 1 (May 29, 2001 survey) current measurements illustrate a mean northward flow, with an onshore component across the shallowest portion of the shoal.

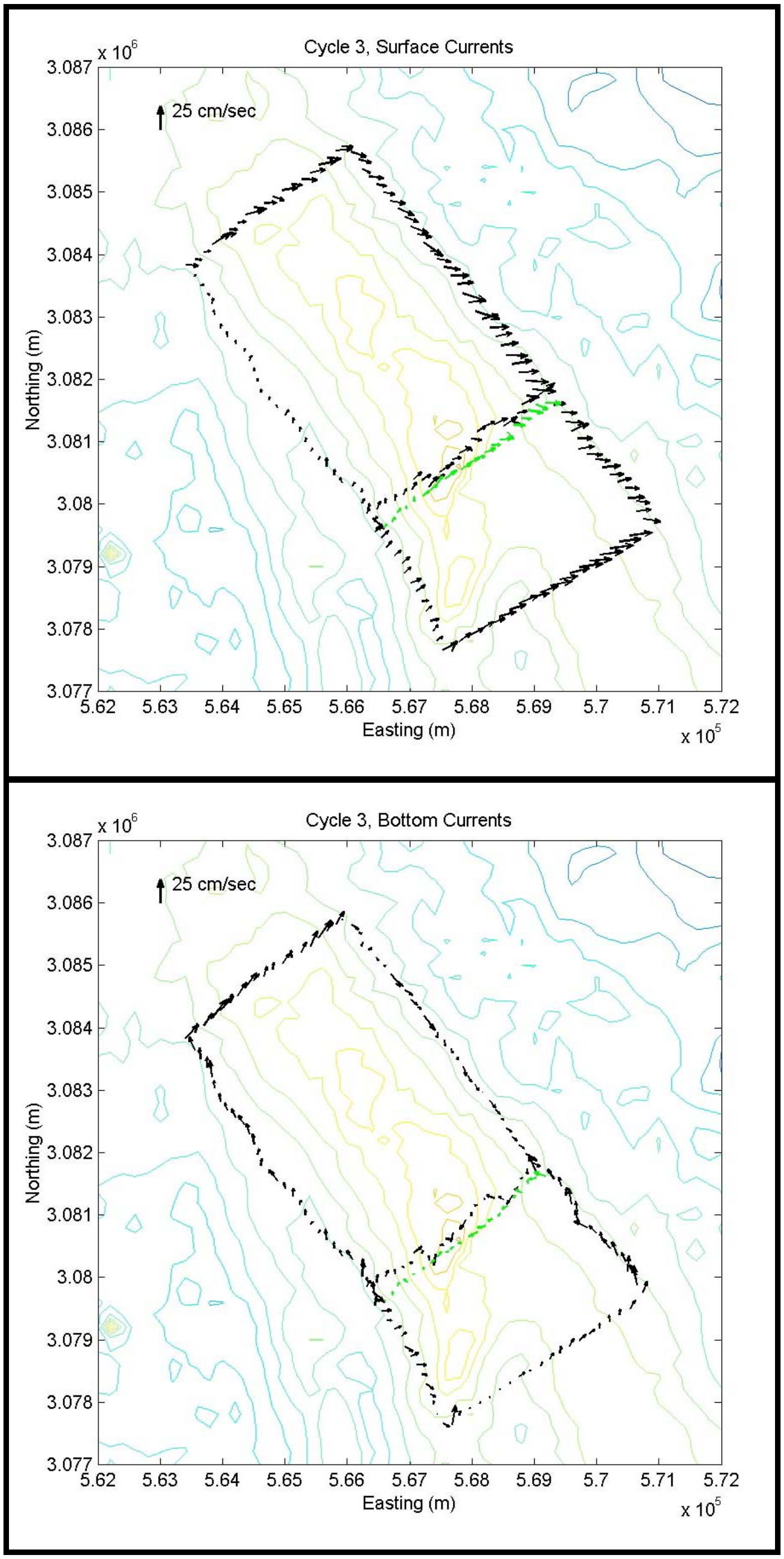

Figure 5-9. During May survey Cycle 3, surface currents on the eastern side of the shoal flowed strongly to the east, while the mean underlying northward flow of bottom currents was impeded. On the western side and across the center of the shoal, surface and near-bottom current magnitudes were reduced significantly.

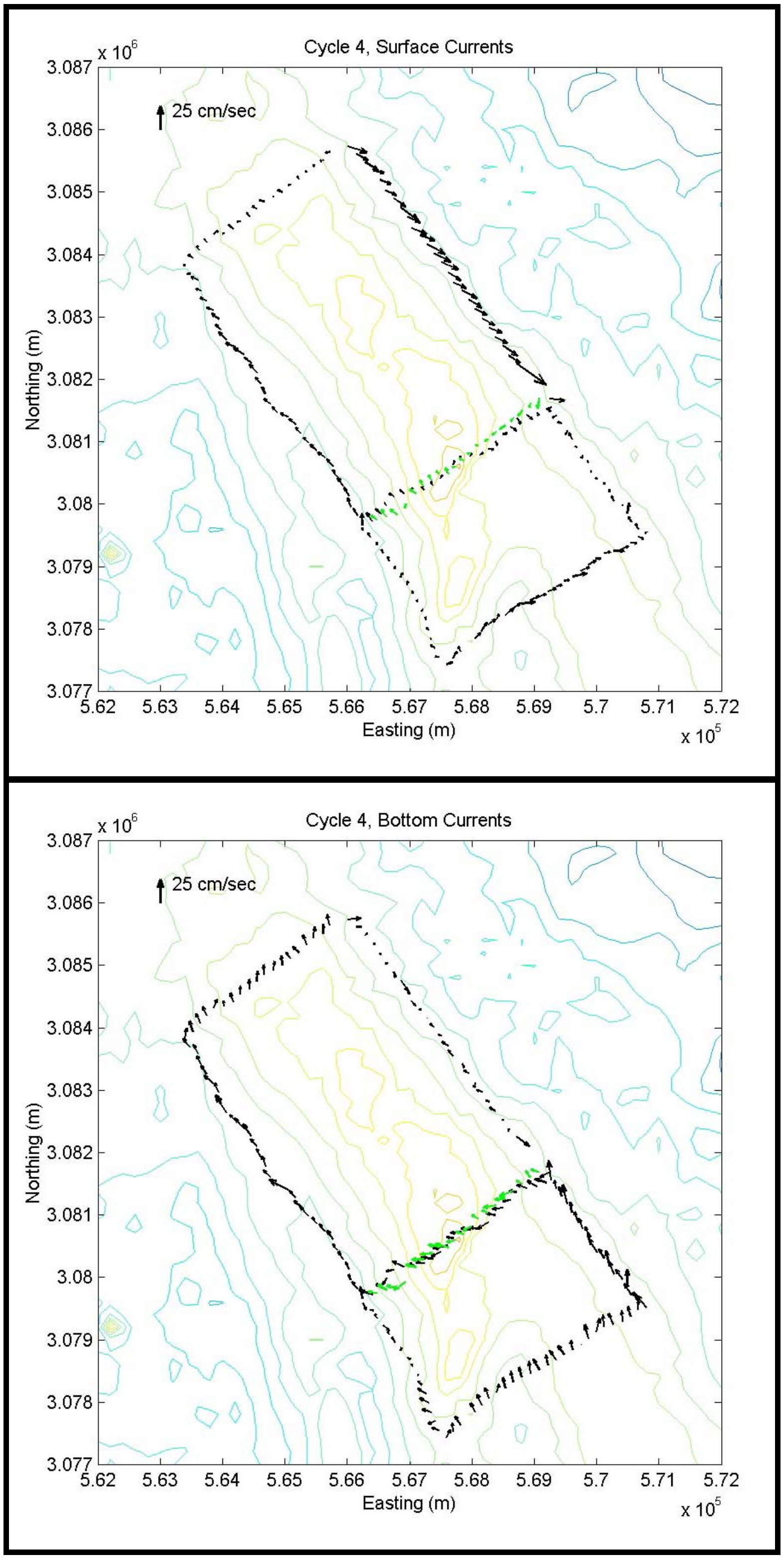

Figure 5-10. During May survey Cycle 4, surface currents slowed due to decreasing winds, but northerly flowing near-bottom currents increased in energy, possibly an indirect result of the Florida Current.

Although current speeds throughout the water column increased with increasing wind speed into Cycle 6, the spatial variability of currents was erratic. Increased wave action, documented in field notes, was likely the cause of extreme current magnitudes and inconsistent flow direction near the end of the survey. Wave-induced flow could not be resolved accurately using ADCP shipboard measurements. A combination of large errors in ADCP measurements and thunder and lightning storms terminated the May 2001 survey.

The water column was weakly stratified at the beginning of the spring survey. Wind-generated storm events and decreased surface water temperatures during winter months commonly results in some mixing. Near-bottom current speeds tended to be slightly slower than surface currents for any given time during the spring survey. Along the perimeter of the shoal, most energy was contained in the along-shelf current component, but across the shoal, cross-shelf currents dominate. Across the shallowest portion of Thomas Shoal, transect Lines 2 and 6 (Figure 5-5), currents seemed to be tidally influenced. Cross-shelf currents flow strongly onshore with speeds up to 25 cm/sec during flood tide (Cycle 1, Figure 5-8). On the ebb tide, cross-shelf currents at speeds of less than 10 cm/sec were directed offshore (Cycle 3, Figure 5-9). These results suggest that onshore cross-shelf currents were favored and enhanced during flood tide cycles. Tidal-induced flows at the southern and northern cross-shelf transect lines were insignificant.

5.1.2.3 Fall 2001 Survey Results

Currents in the vicinity of Thomas Shoal were measured for the fall season on September 4 and 5, 2001. Spring survey transects were repeated to determine the characteristics of seasonal flow variability from spring to fall. Wind speed and direction from the NDBC buoy off Cape Canaveral indicated winds blowing from the south at 5 to 7 m/sec (10 to 14 kts) during the weeks preceding the survey (Figure 5-11). However, winds shifted and blew from the north between August 25 and 30 (5 days before the survey). These northerly winds reached a maximum of 10 m/sec. On September 4 and 5, the wind record showed counterclockwise rotating winds. At the beginning of the survey, strong winds blew from the east-southeast and gradually lost energy as they rotated to the north in the first 12 hours. Wind speeds were below 3 m/sec from 0000 to 1400 hours on September 5. As winds shifted to a more southerly direction at 1500 hours, wind speeds exceeded 4 m/sec throughout the remainder of the survey.

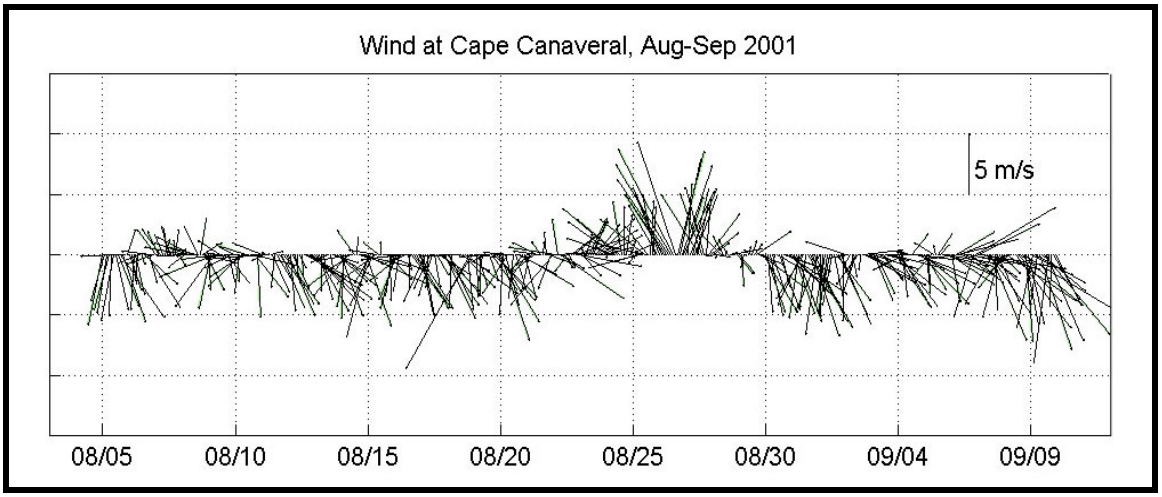

Figure 5-11. Wind conditions prior to and during the September survey measured at the NDBC buoy 20 nm east of Cape Canaveral.

On September 4, the survey began at 1900 hours, just prior to the second high tide of the day. The survey ended on September 5 at approximately 2000 hours, 1 hour prior to the latter high tide, spanning almost two tidal cycles. Maximum tide range on this day was approximately 1.0 m at Cape Canaveral (Figure 5-12). Based on annual tide records, September 4 and 5 correspond to nearly spring tides (maximum tidal range). However, the tidal record shows the 14-day spring tide cycle from August 27 to September 10 has a lower than average maximum range of 1.1 m (Figure 5-12). This reduced tide range may have been due to the period of strong northerly winds in late August.

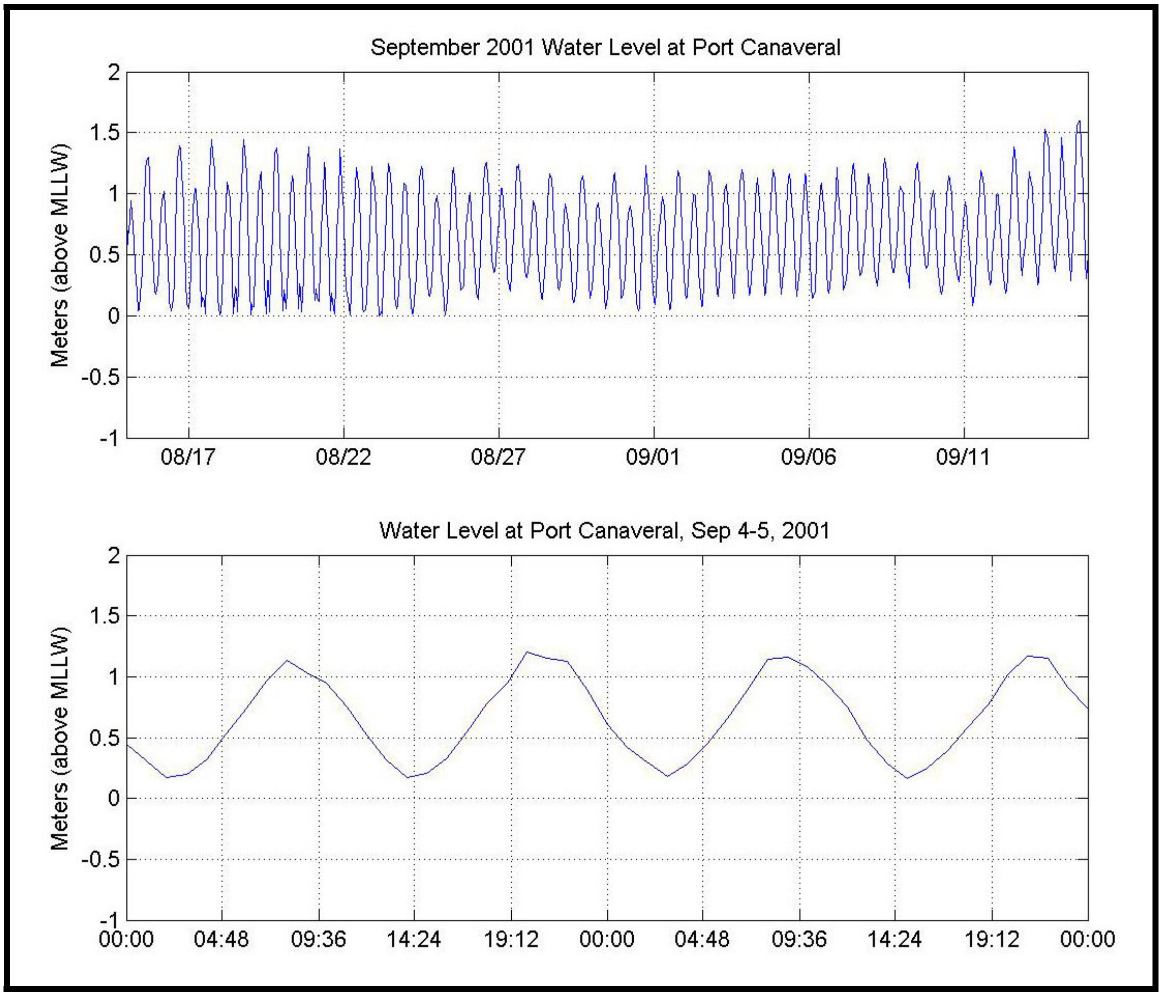

Figure 5-12. September 2001 water elevation measured at the NOS tide gage on the Trident Pier at Port Canaveral; the lower plot illustrates water level during the survey.

September survey results illustrated a mean southerly flow that was altered by wind direction. Leading up to Cycle 1, winds had been blowing out of the east-southeast for several hours. Surface currents on the eastern side and across the center of Thomas Shoal flowed to the west and southwest at approximately 20 cm/sec in response to easterly winds (Figure 5-13). Bottom currents flowed southeast aligned with bathymetry. Opposing surface and bottom current directions suggest Ekman dynamics in the presence of southeast winds. However, rotating winds beginning in Cycle 2 obscure the subtle indication of Ekman circulation. Across the shoal, currents throughout the water column were dominated by onshore cross-shelf flow.

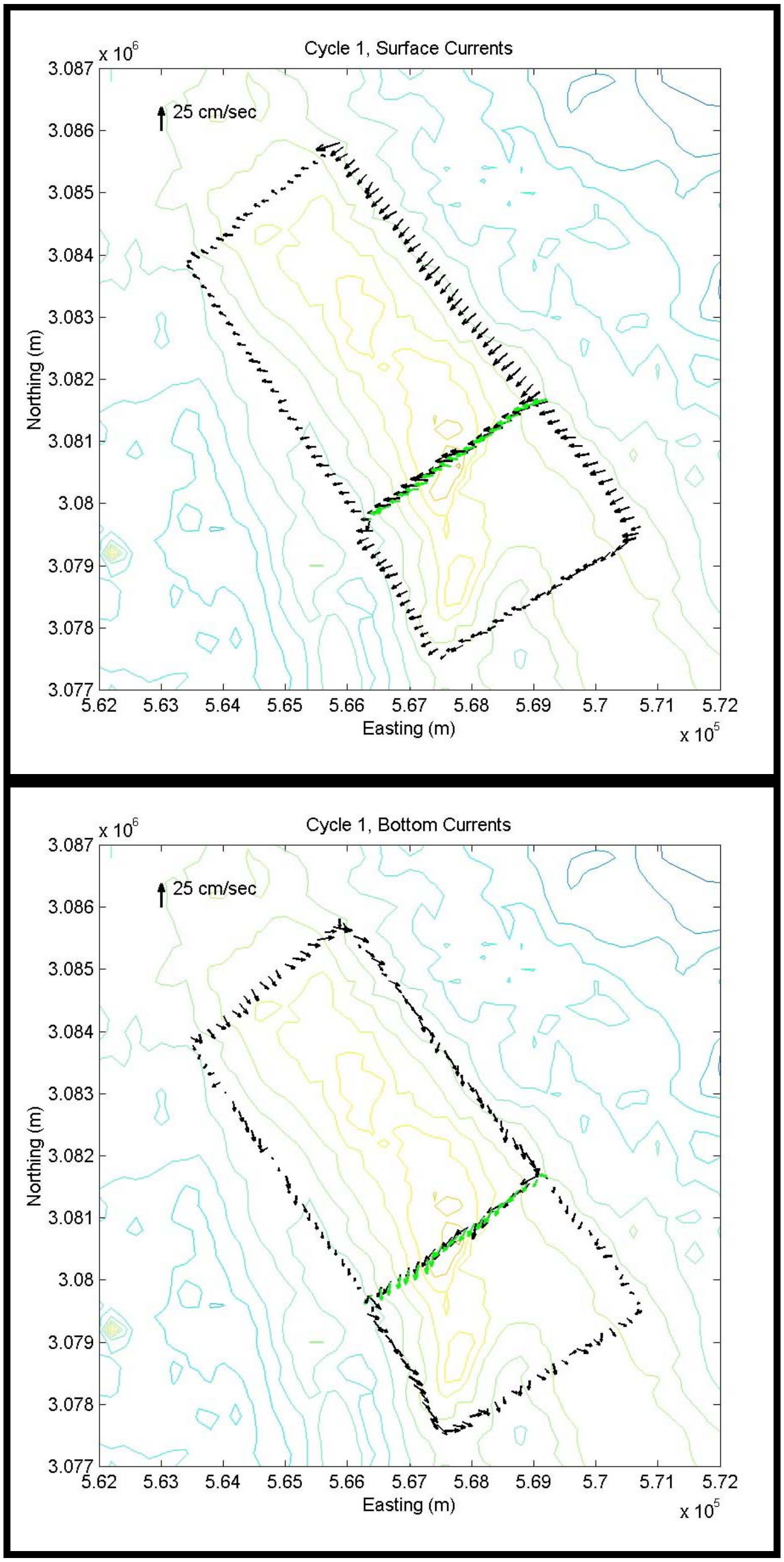

Figure 5-13. During September survey Cycle 1, surface currents on the eastern side and across the center of the shoal flowed to the southwest due to easterly winds. Bottom currents flow southeast, aligned with bathymetry.

Current speeds were strongest (20 to 30 cm/sec) in the presence of northerly winds. During survey Cycles 4 and 5, winds rotated counterclockwise sustaining an average speed of 2 m/sec. Winds blew from the west at the beginning of Cycle 4 (0800, September 5), rotating north in the middle of Cycle 4 (1000 hours), northeast at the beginning of Cycle 5 (1200), and east by the end of Cycle 5 (1500). In response to northerly wind, surface currents gradually increased in speed during Cycle 4 and shifted in direction from south to southeast along bathymetric contours (Figure 5-14). Maximum surface current speeds of 30 cm/sec flowing to the southeast were reached during Cycle 5 (Figure 5-15). Maximum bottom current speeds of 25 cm/sec also were observed during the short period of northerly winds (Figure 5-15). Bottom currents maintained a southerly direction aligned with bathymetric contours throughout the survey, and were enhanced by northerly winds. The response of bottom currents to wind shift was delayed compared with surface currents. During Cycle 4, bottom current speeds were less than 15 cm/sec (Figure 5-14). Bottom current speeds along the eastern side and across the shoal increased in energy during Cycle 5, but remained weak along the western margin of the shoal (Figure 5-15).

Along the perimeter of Thomas Shoal, there was an indication that bottom currents vary with proximity to the shoal. Measurements along Line 7, on the western margin of the shoal, showed an average water depth of 15 m; the shallowest depth across the shoal was approximately 11 m. Flow along Line 7 was weaker than on the eastern margin of the shoal (14 m water depth), and it was directed onshore (Figure 5-15). Weaker bottom currents along the western boundary of the shoal may have resulted from modification of stronger currents as they crossed the shoal (i.e., bathymetric sheltering). In addition, the literature illustrates that wind influence on bottom currents decreases with increasing depth, which may explain the presence of weaker currents along the western margin of the shoal.

Along the shoal perimeter, most of the current energy was contained in the along-shelf component of flow. Figure 5-16 shows vertical profiles of the along-shelf component of flow for survey Line 7, at the western side of the shoal under three wind conditions, to further illustrate wind dependence on currents during the September survey. In the top panel, winds were out of the south, currents were weak, and the water column was relatively homogeneous. Winds out of the east (middle panel) drive stronger along-shelf currents in the upper half of the water column, but bottom currents remain weak. As discussed previously, the strongest surface currents corresponded to northerly winds (lower panel), but bottom currents along this transect remained weak on the leeward side of the shoal, indicating bathymetric sheltering.

At shallow water depths (11 to 14 m) in close proximity to the shoal, the water column was weakly stratified in the presence of southerly or easterly winds. Northerly winds provide mixing, yielding a more homogeneous water column over the shoal. Near-bottom current speeds were slower than surface currents on all transect lines during most cycles of the September survey. Tidal-induced currents had minimal influence on flows in the survey area.

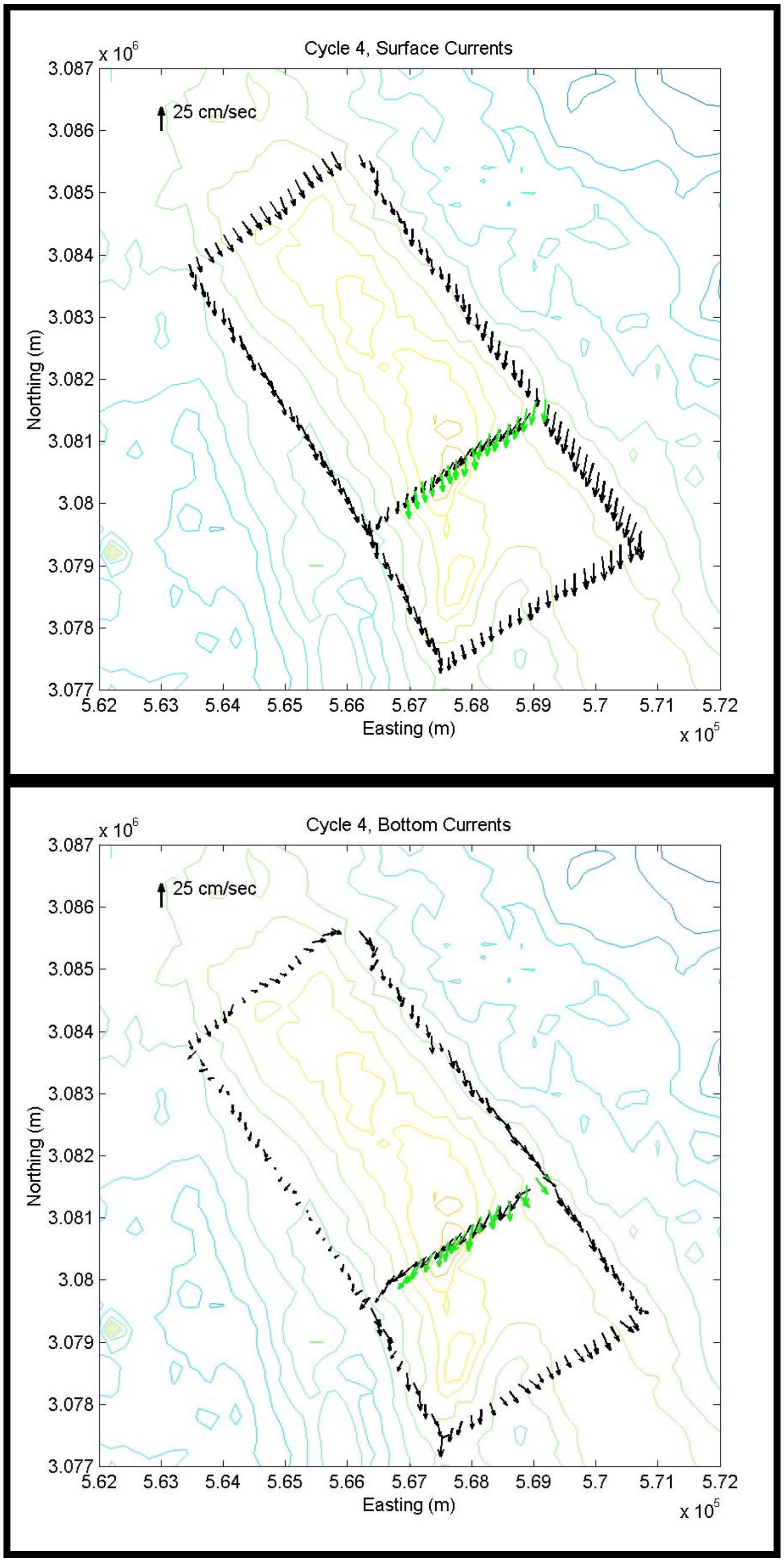

Figure 5-14. In response to the northerly wind, surface currents gradually increase in speed and shift in direction from south to southeast during September survey Cycle 4. Bottom currents do not exhibit a response to this wind shift.

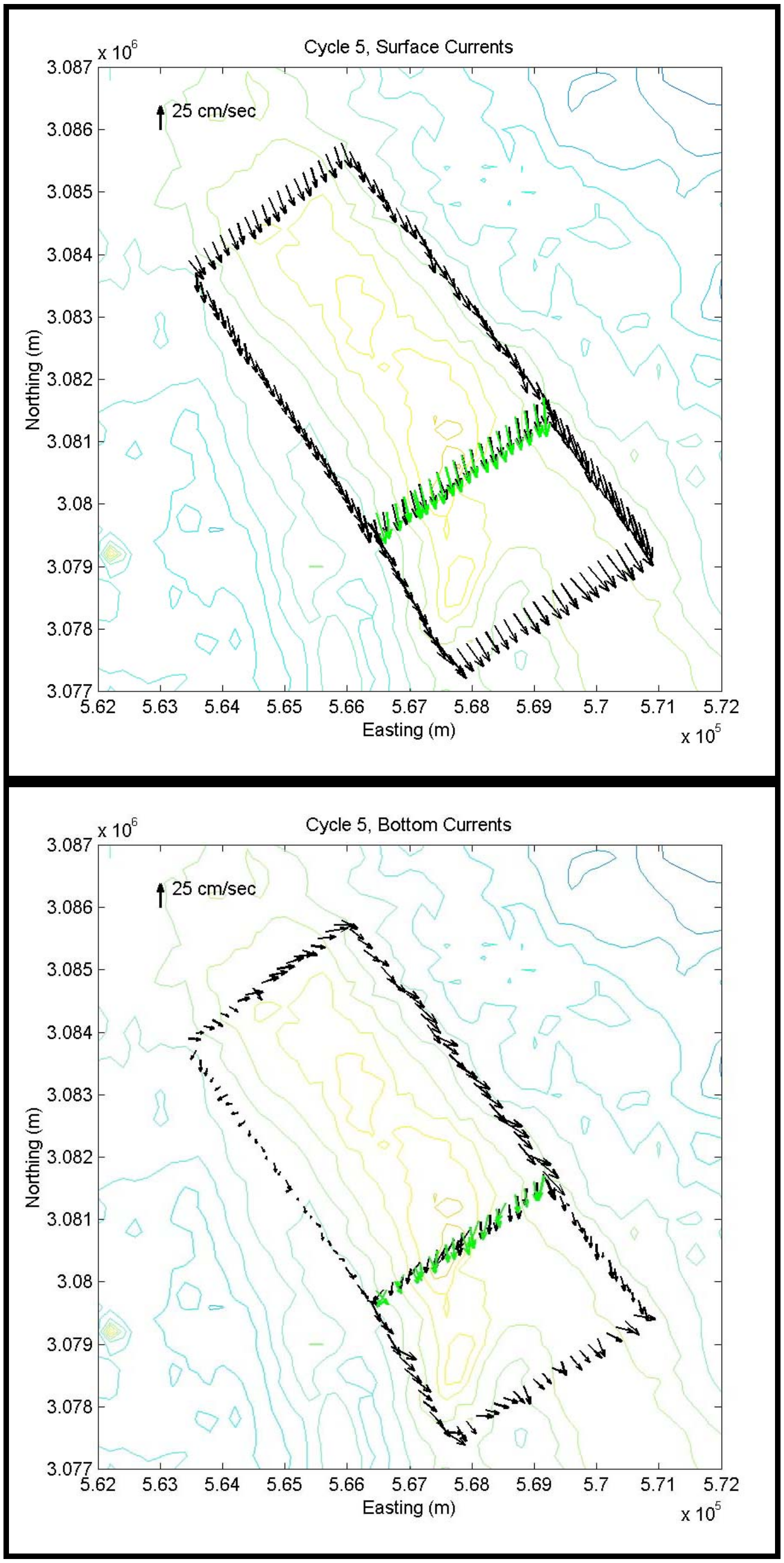

Figure 5-15. Maximum surface current speeds of 30 cm/sec were observed to the southwest and maximum bottom current speeds of 25 cm/sec were reached during September survey Cycle 5 in response to northerly winds.

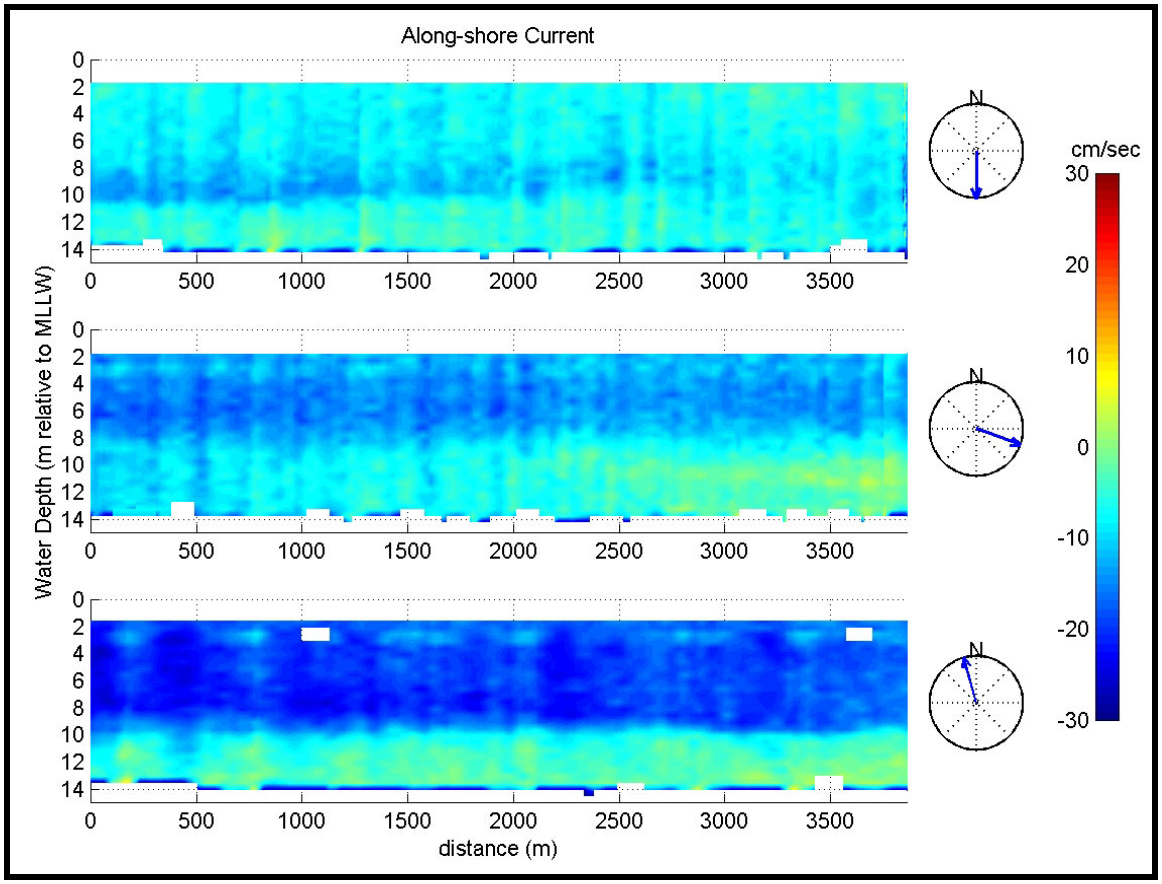

Figure 5-16. Vertical profiles of along-shelf currents measured across Survey Line 7 during three wind conditions indicated by the compass to the right. Positive values (warm colors) indicate currents flowing to the northwest, and negative values (cool colors) indicate currents flowing to the southeast.

5.1.3 Summary of Flow Regimes at Offshore Borrow Sites

Historical current observations and ADCP field surveys indicated that flow regimes in central east Florida were dependent on wind forcing, effects of the Florida Current, and seafloor topography. Tidal currents have minimal influence on flows at borrow site locations.

Circulation patterns along the central east Florida coast near potential offshore borrow sites were investigated using current meter observations obtained offshore St. Lucie Inlet and over Thomas Shoal, seaward of Sebastian Inlet. Analysis of historical data indicated that circulation patterns consisted predominantly of along-shelf currents that reversed direction approximately every 2 to 10 days. Current reversals were found weakly correlated with local wind stress; literature suggested that subtidal variability was due to meanders or spin-off eddies for the Florida Current. Peak speeds were on the order of 40 to 50 cm/sec at mid-shelf and inner-shelf locations and were directed either upshelf (to the north-northwest) or downshelf (to the south-southeast). Strongest currents were most commonly directed to the north. Tidal currents contributed significantly to inner-shelf current observations; however, these observations were obtained near the tidally-dominated St. Lucie Inlet and may not be reflective of inner shelf regions removed from major coastal inlets. ADCP measurements in the vicinity of Thomas Shoal offshore Sebastian Inlet also were dominated by along-shelf flows that correlated with seasonal changes in wind. May survey conditions were dominated by winds from the south, while September survey conditions were characterized by short wind events from the north. Current measurements illustrated a mean flow directed to the north during spring and to the south in fall. This seasonal directionality of flow was supported by historical data and literature regarding observations on the mid-shelf and inner-shelf where sand resource areas have been identified. Strongest currents flowed to the south at 30 cm/sec during the September survey in response to northerly winds.

Seasonal wind variations have been shown to induce downwelling in winter and upwelling in summer for central east Florida. There was an indication of Ekman transport at the beginning of the May and September surveys. However, wind stress variability during both surveys obscured the subtle indications of Ekman circulation. Based on existing studies, northeast winds in winter will create onshore Ekman transport, inducing downwelling; southeast winds, commonly in summer, drive offshore Ekman circulation, creating potential for upwelling (Smith, 1987).

Current variability not well explained by wind stress may be an indirect response to the Florida Current. The Florida Current flows northward past the study area on the outer shelf (Lee et al., 1985). Instabilities in the Florida Current create spin-off eddies that have been documented on the inner shelf (Smith, 1981). Potential influences of the Florida Current were observed in spring survey results, illustrated by a strong northward flowing bottom current in the presence of weak winds and surface currents. Florida Current effects may enhance northerly flows during winter and spring in the study area.

Tidal effects within the study area are not well documented. In shallow waters, over shoals, and adjacent to tide-dominated inlets such as St. Lucie, cross-shelf tides may influence current velocities. May and September field data showed onshore currents dominated across the shoal. During the May survey, onshore currents were enhanced by flood tide. Tidal dependence was not observed during the September survey. On the inner- to mid-shelf, in the vicinity of the sand resource areas, tidal effects are secondary to wind effects.

In the presence of local bathymetric features, such as Thomas Shoal, steering and sheltering of flow across the shoal were observed. Under average conditions, currents were steered onshore across the shoal. In the presence of dominant winds, near-bottom currents flowed parallel to bathymetric contours. Wind-driven currents across local bathymetric features may not be observed on the leeward side of the shoal. For example, during the May survey, east winds drive southwest currents on the eastern margin of Thomas Shoal, but southeast currents were not observed on the western margin.

5.2 OFFSHORE SEDIMENT TRANSPORT

Infilling rates for potential offshore borrow sites 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 time scales (low frequency) was modeled. This analysis provided a method for estimating the combined wave-current friction factor (f_{cw}), which is necessary for computing sediment transport at a borrow site.

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

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

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 near Thomas Shoal provided input conditions for determining borrow site infilling rates. Wave data were extracted from the existing condition model runs at the perimeter nodes of each proposed borrow site. These are the same STWAVE model runs used to determine sediment transport potential at the coastline (see Section 4.0). Wave model input conditions used for each sand resource area are listed in Tables 5-2 through 5-5. Surface current speeds used to determine infilling rates are given in Table 5-6. These currents are based on analyses presented in Section 5.1. Currents were applied in the model based on their percent occurrence. Ambient current directions were set as alongshore and based on the direction of wave propagation for each modeled wave case.

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 5-7.

Table 5-2. Wave model input conditions used to compute offshore sediment transport potential for the borrow site in Area A. STWAVE model output from each modeled condition, and at each borrow site perimeter grid node, was used as input to the wave-current interaction model used to determine bottom sediment transport potential.

Wave Period Band	Peak Wave Direction, θ_p (deg true north)	H_{mo} Wave Height (m)	Mean Peak Wave Period, T_p (sec)	% Occurrence
Band 1	55	1.7	7.7	8.2
	80	1.4	7.7	20.8
	100	1.0	7.7	24.6
	130	1.5	6.3	2.3
Band 2	60	1.7	12.5	6.5
	65	1.6	12.9	28.5
	100	1.5	11.1	3.4

Table 5-3. Wave model input conditions used to compute offshore sediment transport potential for borrow sites in Area B. STWAVE model output from each modeled condition, and at each borrow site perimeter grid node, was used as input to the wave-current interaction model used to determine bottom sediment transport potential.

Wave Period Band	Peak Wave Direction, θ_p (deg true north)	H_{mo} Wave Height (m)	Mean Peak Wave Period, T_p (sec)	% Occurrence
Band 1	25	1.9	6.9	2.3
	45	1.8	7.6	6.5
	65	1.6	7.7	14.2
	90	1.1	7.7	24.7
	105	1.1	6.9	5.7
Band 2	50	1.7	11.4	6.7
	65	1.7	13.9	24.1
	90	1.7	13.4	6.6

Table 5-4. Wave model input conditions used to compute offshore sediment transport potential for borrow sites in Area C. STWAVE model output from each modeled condition, and at each borrow site perimeter grid node, was used as input to the wave-current interaction model used to determine bottom sediment transport potential.

Wave Period Band	Peak Wave Direction, θ_p (deg true north)	H_{mo} Wave Height (m)	Mean Peak Wave Period, T_p (sec)	% Occurrence
Band 1	32	1.6	6.8	4.5
	47	1.5	7.5	12.3
	72	1.3	7.5	15.6
	87	1.0	6.9	11.5
	107	1.1	5.4	4.5
Band 2	52	1.4	12.3	18.4
	62	1.5	13.3	19.4
	87	1.1	11.1	2.0

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

Wave Period Band	Peak Wave Direction, θ_p (deg true north)	H_{mo} Wave Height (m)	Mean Peak Wave Period, T_p (sec)	% Occurrence
Band 1	50	1.4	6.9	7.0
	65	1.3	7.4	15.3
	90	1.2	6.9	14.1
	110	1.2	5.5	5.9
	135	1.1	4.9	4.1
Band 2	75	1.3	12.9	24.5
	80	1.3	13.0	12.6

Table 5-6. Surface current speeds used to compute offshore sediment transport potential based on the analyses in Section 5.1.

Current Speed (cm/sec)	Exceedence Occurrence (%)
54	0.1
39	2
32	5
25	10
16	25
12	50

Table 5-7. Borrow site characteristic depths and bottom sediment grain sizes used as bottom sediment transport potential model input.

Borrow Site	Average Bottom Depth (m)	Sediment Size, d_{10} (mm)	Sediment Size, d_{50} (mm)
A1	10.6	0.70	0.32
B1	13.9	1.15	0.60
B2	12.2	1.49	0.47
C1 north	13.0	1.96	0.61
C1 south	12.9	0.62	0.29
D2	18.7	0.50	0.31

5.2.3 Infilling Model Results

Infilling rates computed for six central east Florida borrow sites represent the total potential transport magnitude into each of the sites (Table 5-8). These results likely represent an upper bound for sediment transport at each site, assuming linear wave dynamics and an unlimited sediment supply. Of the six modeled borrow sites, Site A1 has the greatest infilling rate as a result of a combination of factors, including its shallow depth relative to other sites and its large perimeter. Because the borrow site is in relatively shallow water, wave-induced currents and wind-driven currents are large, and more sediment can be mobilized in the proximity of the borrow site. Sites that have a larger perimeter generally will trap more sediment over a given period. Furthermore, sediment grain size also affects sediment mobility, such that relatively smaller gain sizes at Site A1 would tend to be more mobile than larger sediment identified at other areas.

Table 5-8. Characteristic dimensions, computed borrow site infilling rates, and estimated time to fill based on total proposed excavated volume.

Borrow Site	Borrow Site Area (m^2)	Excavated Volume ($x\ 10^6\ m^3$)	Average Depth (m)	Infilling Rate (m^3/yr)	Infilling Time (yr)
A1	$5.4x10^6$	13.6	10.6	538,000	25
B1	$4.6x10^6$	11.0	13.9	152,000	141
B2	$3.5x10^6$	7.6	12.2	407,000	54
C1 north	$5.2x10^6$	5.8	13.0	152,000	73
C1 south	$4.7x10^6$	8.8	12.9	98,000	122
D2	$2.2x10^6$	4.1	18.7	5,000	770

Total infilling times presented in the last column of Table 5-8 were computed using the total design excavated volume divided by computed infilling rates. As such, they represent the length of time required to fill a site that is excavated to the total design depth during a single dredging event. Site D2 has the longest total infilling time, resulting primarily from the small infilling rate computed for this area and large average water depth. Site A1 has the shortest infilling time due primarily to its large computed infilling rate and shallow depth. These estimated infilling times are most useful as a relative guide for borrow site infilling rather than an absolute indicator of exactly how long it takes for the borrow site to fill.

6.0 BIOLOGICAL FIELD SURVEYS

6.1 BACKGROUND

Field surveys for biological characterization provided environmental data in and near the nine sand resource areas offshore central east Florida. Data were collected concerning water column and sediment parameters, infauna, soft bottom epifauna and demersal fishes, and hard bottom epibiota and demersal fishes. The following sections provide the methods, results, and discussion for the biological field surveys.

6.2 METHODS

6.2.1 Survey Design

The objective of the biological field surveys was to characterize benthic ecological conditions in and near the nine sand resource areas (Figure 6-1). Benthic characterization focused on soft bottom (i.e., sediment, infauna, epifauna and demersal fishes) and hard bottom (i.e., epibiota and demersal fishes) parameters. Supporting data collected in the soft bottom areas consisted of water column profiles.

Total numbers of samples by type originally proposed for the biological field surveys were as follows:

SAMPLE TYPE	SURVEY 1	SURVEY 2
Soft Bottom		
Water Column		
Sea-Bird CTD	18 Stations	18 Stations
Sediment and Infauna		
Shipek Grab	62 Stations (1 grab/station)	62 Stations (1 grab/station)
Sediment Only		
Shipek Grab	48 Stations (1 grab/station)	48 Stations (1 grab/station)
Epifauna/Demersal Fishes		
Mongoose Trawl	18 Transects	18 Transects
Hard Bottom		
Epibiota/Demersal Fishes		
Video Camera	9 Line Miles	9 Line Miles
Still Camera	180 Photographs	180 Photographs

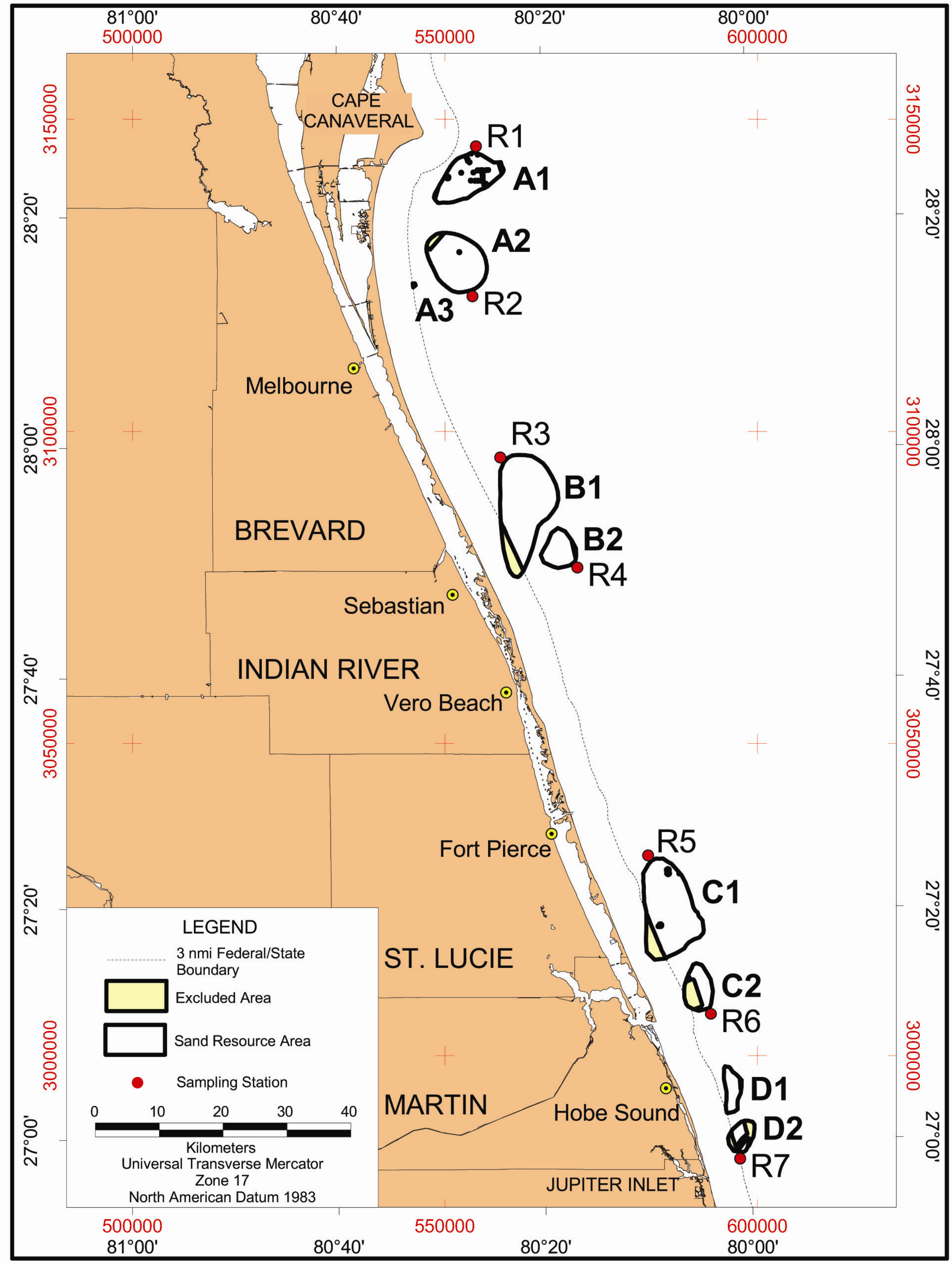

Figure 6-1. Nine sand resource areas (A1, A2, A3, B1, B2, C1, C2, D1, and D2) and seven adjacent stations (R1 through R7) relative to the central east Florida coast.

Actual sampling for the biological surveys is described in subsequent subsections. Two soft bottom and two hard bottom surveys were conducted on dates described in Section 6.2.2.1. Table 6-1 summarizes the actual soft bottom sampling and lists the sand resource areas and adjacent stations along with corresponding water depths, sample types, and number of stations. Actual hard bottom sampling is described in Section 6.2.1.5.

Table 6-1. Actual soft bottom sampling during the central east Florida biological field surveys.

Sand Resource Area (A1, B1, C1, D1, etc.) and Adjacent Station (R1, R2, etc.)	Water Depth (m)	Soft Bottom Sample Type							
		Water Column Profiles		Shipek Grab				Trawl Transects for Epifauna and Fishes	
				Sediment-Only Samples		Sediment/ Infaunal Samples			
		Survey 1	Survey 2	Survey 1	Survey 2	Survey 1	Survey 2	Survey 1	Survey 2
A1	14-18	2	2	6	6	7	7	2	2
A2	15-18	2	2	8	8	7	7	2	2
A3	13-15	2	2	0	0	3	3	2	2
B1	12-20	2	2	14	14-1	13+1	13+1	2	2
B2	10-15	2	2	3	3	4	4	2	2
C1	8-21	2	2	12	12	12	12	2	2
C2	14-21	2	2	2	2	3	3	2	2
D1	19-33	2	2	2	2	3	3	2	2
D2	15-50	2	2	1	1	3	3	2	2
R1	15					1	1		
R2	19					1	1		
R3	17					1	1		
R4	13					1	1		
R5	14					1	1		
R6	20					1	1		
R7	23					1	1		
Total Number of Stations		18	18	48	47	56 + 7 = 63	56 + 7 = 63	18	18

6.2.1.1 Spatial Data Files and Exclusionary Mapping

Spatial data files of environmental features (e.g., sand resource areas, hard bottom areas, shipwrecks, submarine cables, etc.) and exclusionary mapping were used to design the field surveys as discussed in detail in Appendix E. The purpose of exclusionary mapping was to ensure that sampling would include areas in Federal waters shallower than 30 m and exclude areas that were unlikely to be dredged due to the presence of environmental features.

6.2.1.2 Water Column

Eighteen water column profiles were made during each of two soft bottom surveys at locations illustrated in Figures 6-2 through 6-6 and listed in Appendix F1. Parameters measured were conductivity, temperature, and depth. A water column profile was made at the beginning point of each trawl transect prior to actual trawling (see Section 6.2.1.4 for the rationale used for selecting trawl locations).

6.2.1.3 Sediment and Infauna

For each of two soft bottom surveys, 62 stations originally were proposed for samples that would be analyzed for both sediment and infauna, and 48 additional stations originally were proposed for sediment analysis only. The following rationale was used to determine the number of samples that would be collected in the sand resource areas and at adjacent stations. The results of applying this rationale are illustrated in Figures 6-1 through 6-6. The locations also are listed in Appendix F1.

Of the original 62 stations, 7 stations were assigned to adjacent stations near the sand resource areas, leaving 55 stations to be taken within the nine sand resource areas. The 7 adjacent stations were located so that samples would be collected approximately 1,000 m north or south of the nine sand resource areas at median water depths, as illustrated in Figure 6-1.

To determine the number of samples to collect in each sand resource area for sediment and infaunal analyses during each survey, the surface area and percent of the total surface area for each of the sand resource areas were calculated before and after exclusionary mapping was completed (Table 6-2). The percent of the total surface area remaining after exclusionary mapping for each of the sand resource areas then was multiplied by 44 stations, leaving 11 stations for discretionary placement within the sand resource areas. Multiplication by 44 stations indicated that some sand resource areas had none or too few samples due to very small surface areas relative to the total surface area (i.e., Sand Resource Area A3 had 0 samples, C2 had 2 samples, D1 had 2 samples, and D2 had 1 sample; see Table 6-2). Therefore, 7 of the 11 discretionary samples were added to the sample numbers for Sand Resource Areas A3, C2, D1, and D2 such that there would be 3 stations in each of these sand resource areas. This brought the total number of samples to be analyzed for both sediment and infauna to 51. Four of the 11 discretionary samples remained for later location.

Whereas 62 stations were proposed for samples that would be analyzed for both sediment and infauna, 48 additional stations were proposed for sediment analysis only for each survey. The purpose of collecting these additional 48 sediment samples was to extend the interpretation of the infaunal data. To determine the number of samples to collect during each survey in each sand resource area for sediment analysis only, the percent of the total surface area remaining after exclusionary mapping for each of the sand resource areas was multiplied by 48 stations (Table 6-2).

Attention then was directed to selecting locations for the 51 samples that would be analyzed for both sediment and infauna and the 48 samples that would be analyzed for sediment only. The goal in placement of the stations was to provide broad spatial and depth coverage within the sand resource areas and, at the same time, ensure that the samples

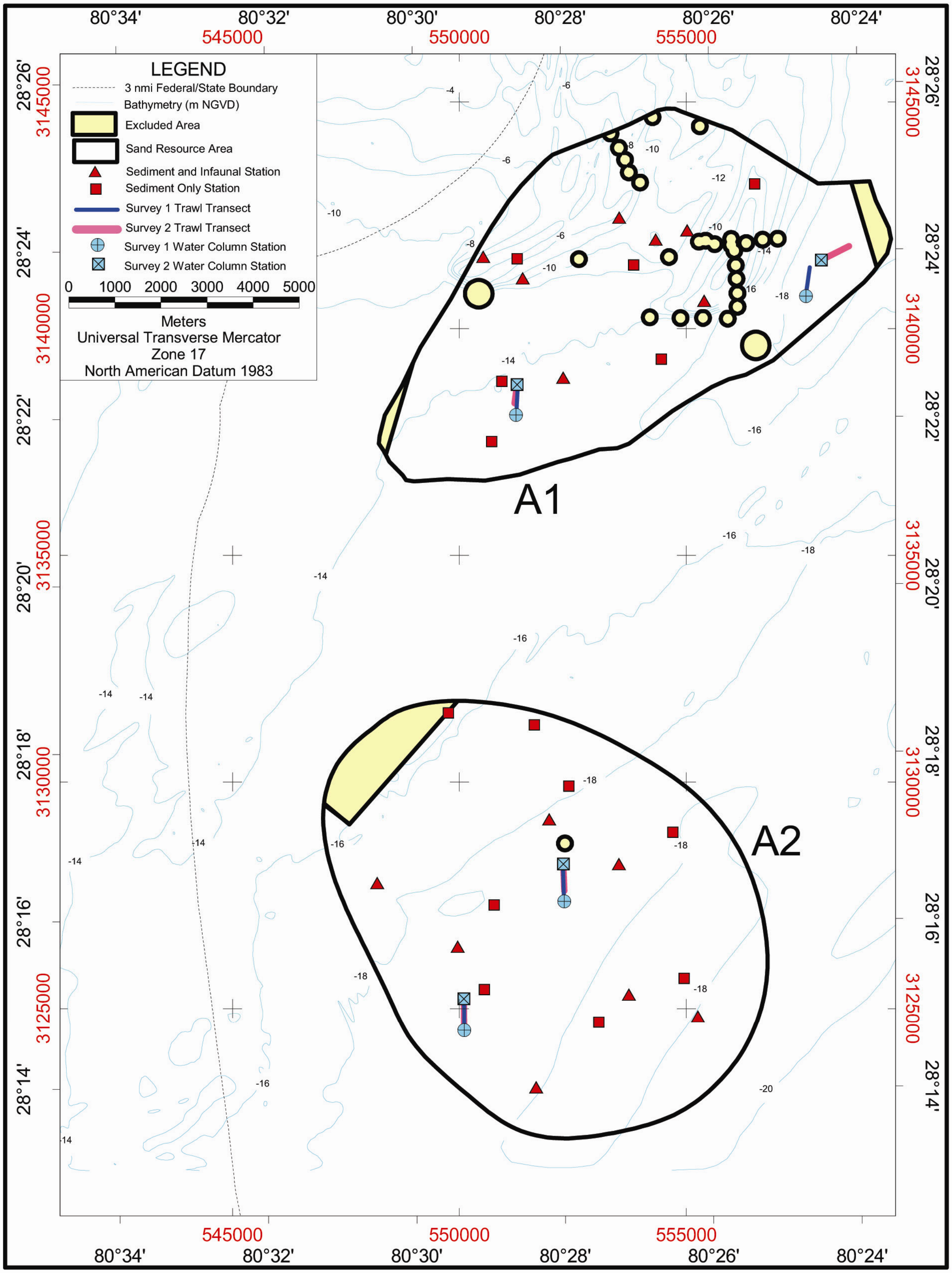

Figure 6-2. Sampling locations for Sand Resource Areas A1 and A2.

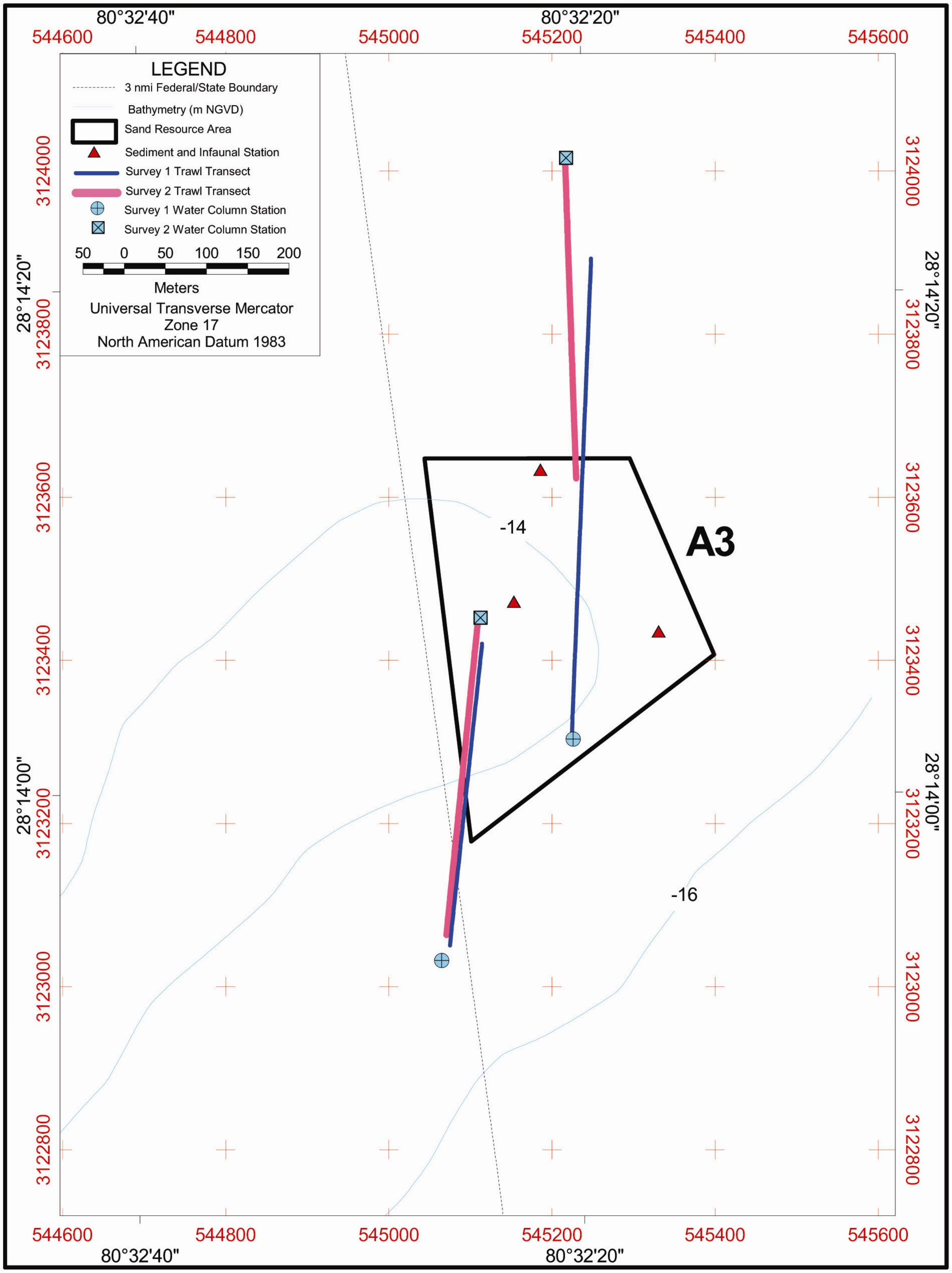

Figure 6-3. Sampling locations for Sand Resource Area A3.

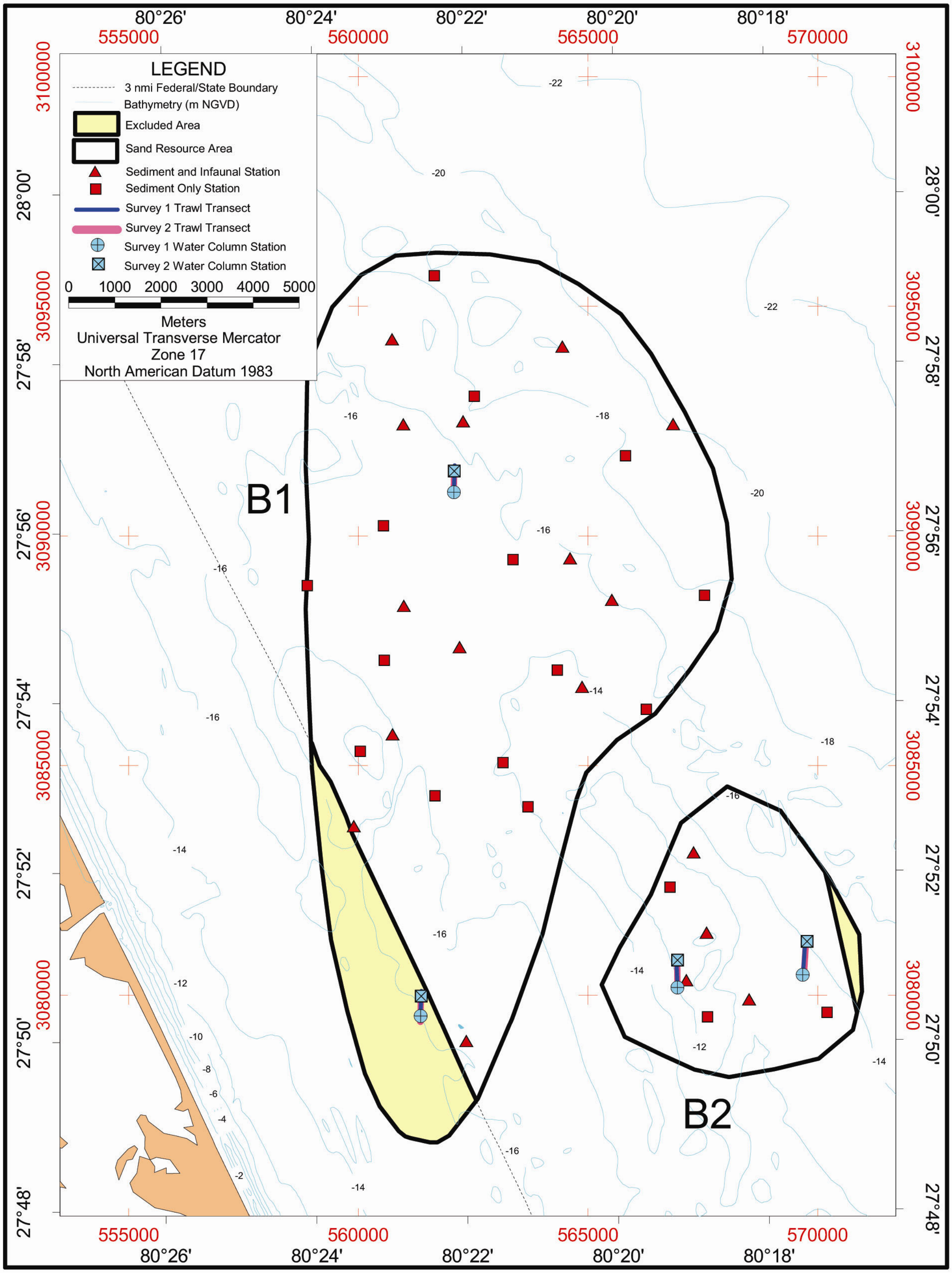

Figure 6-4. Sampling locations for Sand Resource Areas B1 and B2.

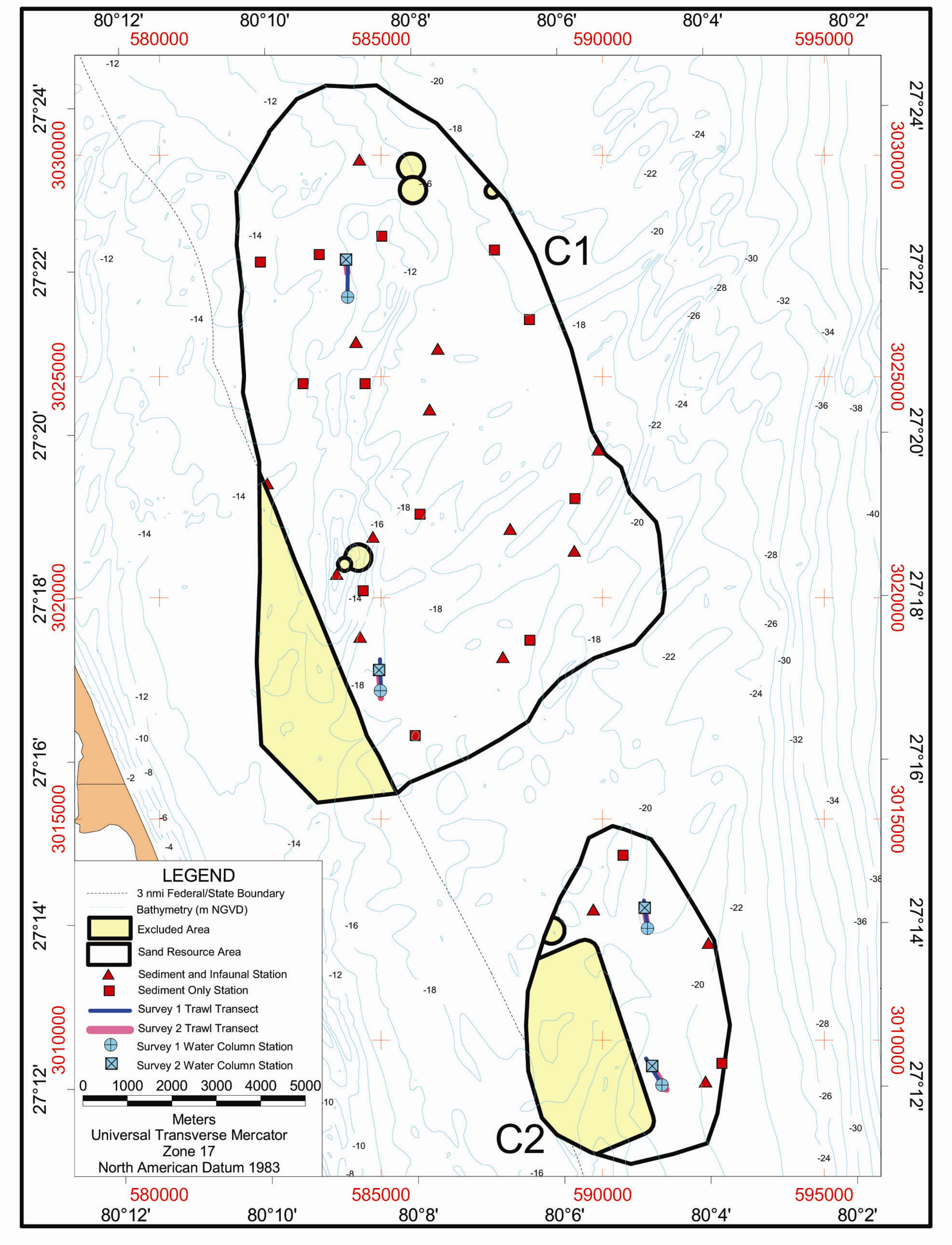

Figure 6-5. Sampling locations for Sand Resource Areas C1amd C2.

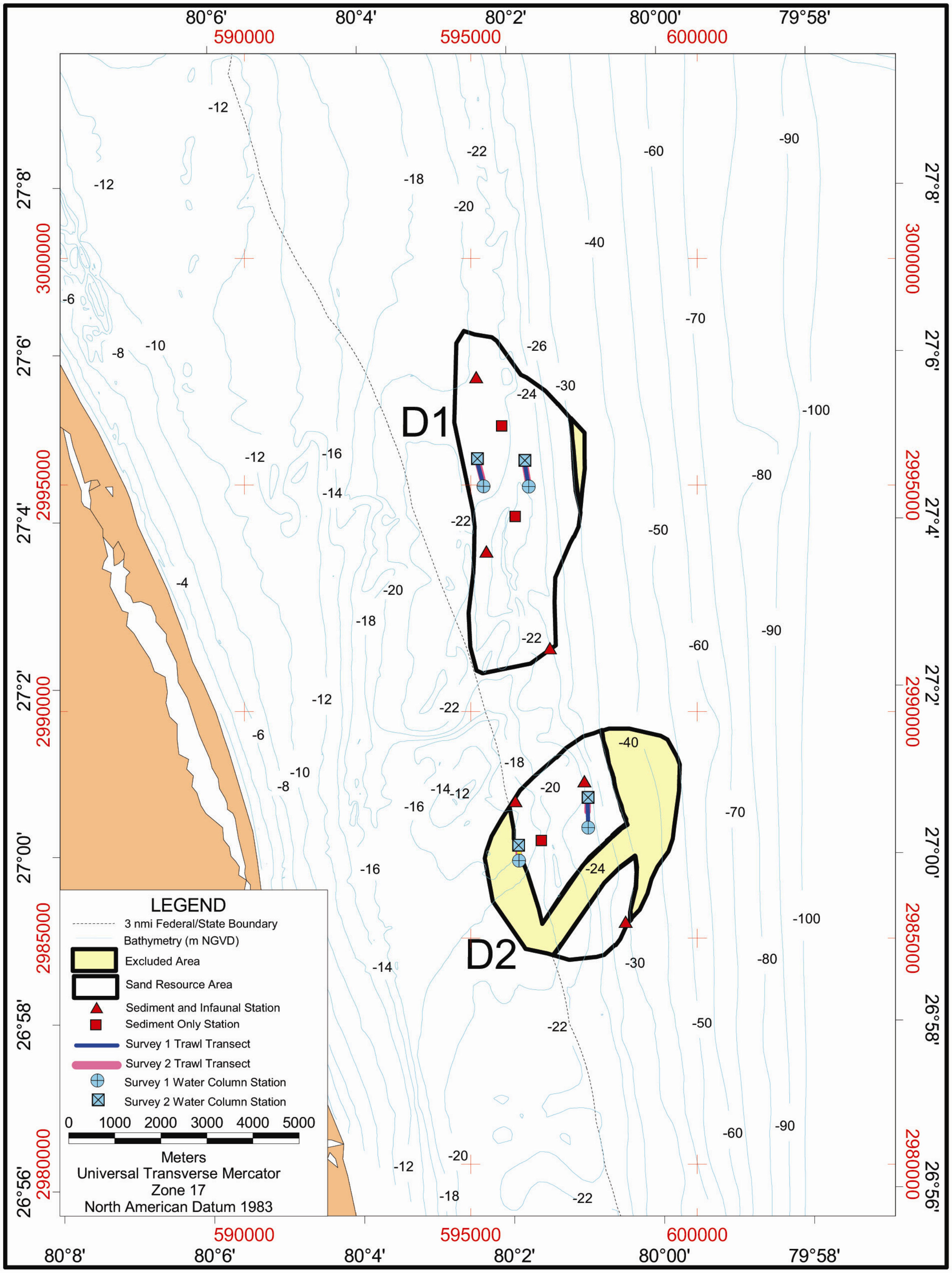

Figure 6-6. Sampling locations for Sand Resource Areas D1 and D2.

Table 6-2. Summary of rationale for allocating sediment/infaunal and sediment-only samples inside the sand resource areas for each survey (seven additional sediment/infaunal samples were allocated to seven adjacent stations [1 sample/adjacent station] outside the sand resource areas for each survey).

Sand Resource Area	Original Area (m^2)	Area Excluded (m^2)	Percent Area Excluded	Remaining Area (m^2)	Percent Area Remaining	Percent of Total Area	Sediment/Infaunal Samples				Sediment-Only Samples Based on 48 Total
								Discretionary Samples			
							Based on 44 Total Samples	Adjustment for 3 Sample Minimum	Adjustment to Sample Shoals	Based on 55 Total Samples	
A1	53,289,280	2,993,781	6	50,295,498	94	13	6	0	1	7	6
A2	68,279,893	3,081,888	5	65,198,004	95	17	7	0	0	7	8
A3	188,789	0	0	188,789	100	0	0	3	0	3	0
B1	122,397,880	11,708,428	10	110,689,451	90	29	12	0	1	13	14
B2	24,997,834	762,234	3	24,235,600	97	6	3	0	1	4	3
C1	108,776,177	11,517,985	11	97,258,192	89	25	11	0	1	12	12
C2	26,421,335	9,687,302	37	16,734,033	63	4	2	1	0	3	2
D1	14,674,932	331,512	2	14,343,420	98	4	2	1	0	3	2
D2	15,355,029	7,640,912	50	7,714,117	50	2	1	2	0	3	1
	434,381,148	47,724,043	11	386,657,105	89	100	44	7	4	55	48

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). The ArcView extension “Sample” by Quantitative Decision was used to create sampling grids with cell sizes appropriate for the number of samples required for an area. Grids were placed over figures of each sand resource area. One sampling station then was randomly placed within each grid cell of each sand resource area such that sediment and infaunal sample cells alternated with sediment-only sample cells. 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 99 sample locations.

The 51 locations for collecting samples that would be analyzed for both sediment and infauna then were examined to determine where best to place the remaining 4 of the 11 discretionary stations. Because the 51 locations were randomly located, there were cases where isobaths indicated that high points of shoals would not be sampled. Therefore, the remaining four discretionary stations were located on the tops of shoals in Sand Resource Areas A1, B1, B2, and C1.

All sediment and infaunal samples were collected according to the previously described plan except for three samples, two of which were sediment/infaunal samples and one being a sediment-only sample. An extra sediment/infaunal sample was collected in Area B1 during both Surveys 1 and 2. One sediment-only sample was not collected in Area B1 during Survey 2 (Table 6-1).

6.2.1.4 Soft Bottom Epifauna and Demersal Fishes

Eighteen mongoose trawl transects for epifauna and demersal fishes were made during each of two soft bottom surveys at locations illustrated in Figures 6-2 through 6-6 and listed in Appendix F1. One north-south transect was placed near the eastern portion and one north-south transect was placed near the western part of each sand resource area to allow characterization of existing assemblages with respect to water depth.

6.2.1.5 Hard Bottom Epibiota and Demersal Fishes

Nine line miles of video camera data and 180 still photographs were proposed for each hard bottom survey. Totals of 23.5 line miles and 700 still photographs actually were collected during the two hard bottom surveys. One hard bottom survey was near southern Sand Resource Areas C2, D1, and D2 and the other survey was near the more northern Areas B1 and B2. The general locations of these sand resource areas are illustrated in Figure 6-1. Figures showing the specific locations of hard bottom video and still photography transects are provided in Section 6.3.4.

6.2.2 Field Methods

6.2.2.1 Vessel and Survey Dates

Both soft bottom field surveys were conducted aboard the R/V GEOQUEST, which is operated by the Florida Geological Survey. The September 2000 Survey 1 was mobilized on 7 September, conducted from 8 to 14 September, and demobilized on 15 September

2000. The June 2001 Survey 2 was mobilized on 30 May, conducted from 31 May to 4 June, and demobilized on 4 June 2001.

Because water clarity was unsuitable during the September 2000 Survey 1 and video equipment problems prevailed during the June 2001 Survey 2, hard bottom photodocumentation data (i.e., video and still photographs) were collected during two separate field surveys. The first hard bottom survey covering southern Areas C2, D1, and D2 was conducted on 18 April 2002 from the M/V THUNDERFORCE owned by M&S Enterprises, Inc. The second survey covering northern areas in and around Areas B1 and B2 was conducted on 7 October 2002 from a Parker outboard work boat owned by Continental Shelf Associates, Inc. (CSA).

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, the ship's position was displayed in real-time on a monitor affixed to a counter top in the wheelhouse. 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

Conductivity, temperature, and depth (CTD) were measured with a Sea-Bird electronic CTD unit. Continuous profiles were made from the water surface to the bottom.

6.2.2.4 Sediment and Infauna

Sediment and infaunal samples were taken with a Shipek grab. Once a sample was deemed acceptable (i.e., adequate sample quantity), a subsample of sediment was removed with a 5-cm diameter acrylic core tube and placed in a labeled plastic bag for analyses. This sediment sample was stored at 4^{o}C (i.e., on ice). If infauna were to be analyzed from the sample, then the remainder of the grab sample was sieved through a 0.5-mm sieve for infaunal analyses. The infaunal sample was placed in a container and preserved in 10% formalin with rose bengal stain.

6.2.2.5 Soft Bottom Epifauna and Demersal Fishes

A 7.6-m mongoose trawl was towed for 10 min (bottom time) along transect lines. 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 and identified to the lowest practical taxon. Any specimens that proved difficult to identify accurately in the field were placed in 10% formalin and transported to the laboratory.

6.2.2.6 Hard Bottom Epibiota and Demersal Fishes

During the April 2002 hard bottom survey of the southern portion of the study area, observations were made and recorded with underwater video and still cameras mounted on a standard tow sled. Video and still cameras were aligned so that both had the same field of view at the time of shutter activation. Both cameras could be aimed at varying degrees below the horizontal using a pan-and-tilt mechanism. Video observations were recorded continuously. Qualitative photographs were taken at the discretion of the on-board biologist. The sled was towed above the bottom at vessel speeds of 1.7 to 3.0 m/s (0.9 to 1.5 kn).

During the October 2002 survey, hard bottom areas were characterized using CSA's mini underwater video/still camera system. This system is equipped with still and video cameras mounted on a fixed frame of an aluminum sled. This sled was either towed slowly or allowed to drift across pre-plotted hard bottom areas in or around the sand resource areas. The path covered by each camera tow was logged into the Hypack navigation system. Video was recorded continuously and still photographs were taken selectively by an on-board biologist.

6.2.3 Laboratory Methods

6.2.3.1 Sediment

Sediment sample analysis consisted of drying a sample and providing a visual description of texture and lithology. Grain size analysis was conducted in accordance with American Society for Testing and Materials (ASTM) Standard D-442. A sediment sample was removed from a collection bag, wet weighed to confirm sufficiency of sample size, and wet sieved through a 62.5-micron screen to separate the clay/silt fraction from sand. The clay/silt fraction was analyzed using standard pipette procedures to determine the size distribution (Folk, 1980).

After wet sieving, the coarse fraction retained on the screen was dried and weighed. The retained fraction was passed through a 2-mm screen to remove gravel sized material (>2 mm in diameter). The weight of the gravel-sized fraction was recorded.

The coarse fraction (the portion left behind after wet sieving and gravel separation) then was weighed, and the gravel and sand fractions were combined. The combined sample was passed through a stack of 0.25-phi screens with openings ranging from -2 to 4 phi. If the -2 phi fraction was greater than 5% of the sample, the material collected on the -2 phi screen was passed through a second stack of sieves, consisting of screens arranged at 0.5-phi intervals ranging from -4 to -2 phi in size. Weight percent collected on each screen was calculated and recorded. Graphical and statistical parameters were determined for each sampling distribution.

Carbonate content was determined for sediment samples from Survey 1. After determining the overall grain size distribution, a sediment sample was recombined then digested in hydrochloric acid. After digestion, the sample was wet sieved through a 63-micron mesh, dried, weighed, and then dry sieved. The fraction remaining on each sieve then was weighed to determine the grain size distribution of the non-carbonate content. The weight percent of the non-carbonate fraction was subtracted from the overall weight percent for each sieve interval to determine the carbonate percent assigned to that interval. Cumulative weight percent for the carbonate fraction then was calculated.

6.2.3.2 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 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 identification level (LPIL) 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.

6.2.3.3 Soft Bottom Epifauna and Demersal Fishes

Formalin-preserved epifauna and demersal fishes were rinsed in freshwater for 12 hours, then transferred to 70% isopropanol. Specimens were then identified to the lowest practical taxonomic level.

6.2.3.4 Hard Bottom Epibiota and Demersal Fishes

Videotapes collected during the camera sled tows over hard bottom areas were reviewed on a jog shuttle video cassette recorder. The videotapes were replayed using the jog shuttle function, which allowed frame-by-frame viewing when necessary. Qualitative observations of the hard bottom and lists of visually conspicuous epifauna and fishes were generated during these reviews.

6.2.4 Data Analysis

6.2.4.1 Water Column

CTD values were entered into an electronic spreadsheet and tabulated. Depth profiles were plotted for temperature-salinity.

6.2.4.2 Sediment

A computer algorithm was used to determine size distribution and provide summary statistics for each sediment sample using Folk's inclusive graphic measures and Method of Moment calculations. For each sample, grain color, median grain size, and percentages of gravel, sand, silt, and clay were recorded along with a Folk's classification. Percent carbonate was recorded only for Survey 1 samples.

6.2.4.3 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:

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

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. Differences in *H′*, *J′*, and *D* between surveys were assessed using analysis of variance.

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

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 (Bray and Curtis, 1957), which was calculated using the following formula:

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 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.

6.2.4.4 Soft Bottom Epifauna and Demersal Fishes

Raw counts of individual epifaunal and demersal fish taxa were tabulated by sand resource area for both field surveys. These counts were used to construct a sample by taxa data matrix. From this data matrix, a sample similarity matrix was generated using the Bray-Curtis similarity index. A group average cluster analysis was used to cluster the similarity matrix.

6.2.4.5 Hard Bottom Epibiota and Demersal Fishes

Hard bottom areas observed during the two surveys were described qualitatively. Simple substrate categories encountered along the survey transects were matched with navigation data to generate plots relative to the location of each discrete substrate type. Two basic substrate types, sand and hard bottom, were mapped along the hard bottom transects. Secondarily, epibiotal cover was described based on the most conspicuous organisms present, for examples “algal sponge” or “dense octocorals.”

6.3 RESULTS

6.3.1 Water Column

Depth profiles of temperature and salinity for the September 2000 Survey 1 are shown in Figures 6-7 to 6-10. Temperature profiles varied little across all sand resource areas, indicating a well mixed water column. Surface temperatures across stations ranged from 29.7ºC in Area A3 to 27.1ºC in Area C2, whereas bottom temperatures ranged from 28.9ºC in Area A1 to 27.9ºC in Area D2. Bottom salinity was similarly uniform with depth in all areas, averaging about 35.5 parts per thousand (ppt). Surface salinity ranged from 36.9 ppt at Area C1 to 35.3 ppt in Area D1. Bottom values varied little among samples, ranging from 36.2 ppt in Area D2 to 36.7 ppt in Area B1.

Depth profiles of temperature and salinity for the June 2001 Survey 2 are depicted in Figures 6-11 to 6-14. Temperature profiles indicated that bottom waters were generally cooler than surface waters in all sand resource areas. The effect was most pronounced in Areas A, B, and C. Surface temperatures ranged from 27.0ºC in Area B1 to 24.4ºC in Area C1. Bottom temperature values ranged from 26.2ºC in Area D1 to 22.2ºC in Area C2. Salinity did not show the same profile as temperature and maintained a vertical profile in all areas. Surface values ranged from 36.5 ppt in Area A1 to 36.1 ppt in Area D1. Bottom salinities also were very similar among samples and ranged from 36.5 ppt in Area C1 to 36.3 ppt in Areas C2, D1, and D2.

6.3.2 Sediment

Results of the sediment analyses are detailed in Hoenstine et al. (2001a,b). Sediment summary statistics are provided in Appendix F2. Sedimentary characteristics of grab samples taken in the sand resource areas during the surveys consisted of various proportions of gravel, sand, silt, and clay. These proportions were used to determine Folk’s classifications for the individual samples that provide a general picture of the type of sediments found in each sand resource area. Table 6-3 indicates that most samples (68 of 221 samples; 31%) were sand, followed by gravelly sand (63; 29%), slightly gravelly sand (32; 14%), sandy gravel (25; 11%), muddy sand (25; 11%), slightly gravelly muddy sand (7; 3%), and gravel (1; <1%). Within sand resource areas, sediments at stations analyzed for infauna were similar to sediments at stations analyzed for grain size only.

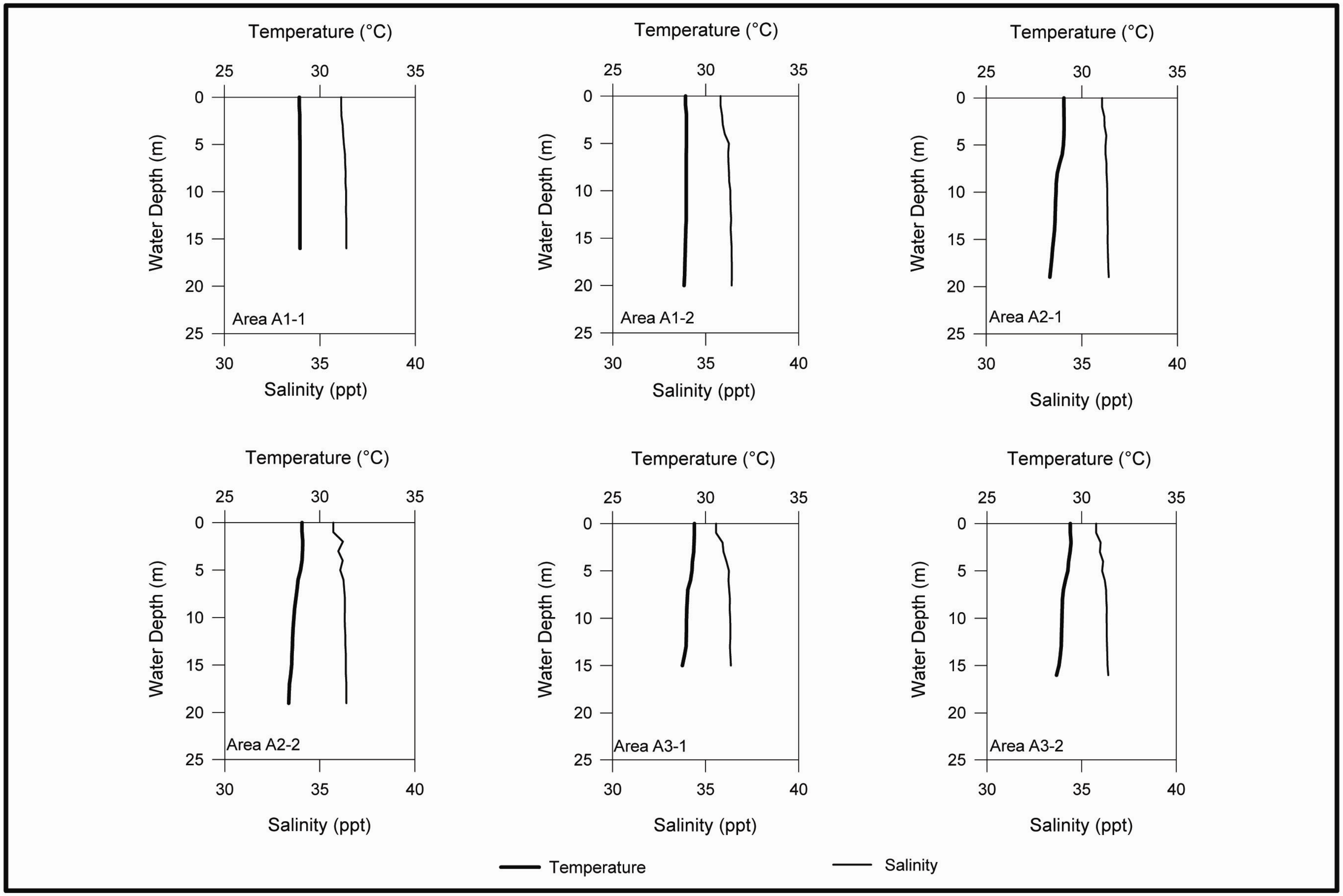

Figure 6-7. Temperature and salinity profiles recorded during September 2000 in Sand Resource Arease A1, A2, and A3.

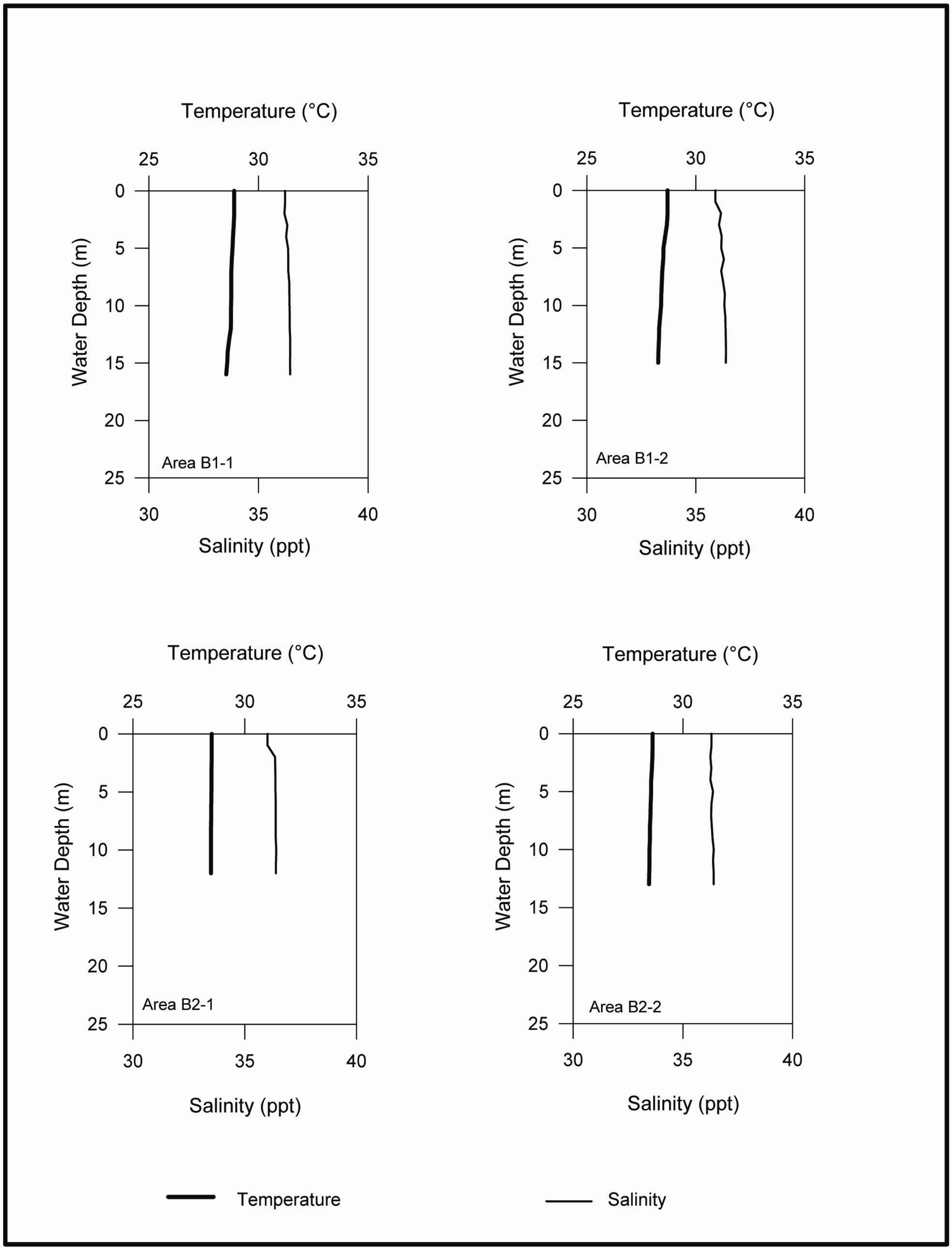

Figure 6-8. Temperature and salinity profiles recorded during September 2000 in Sand Resource Areas B1 and B2.

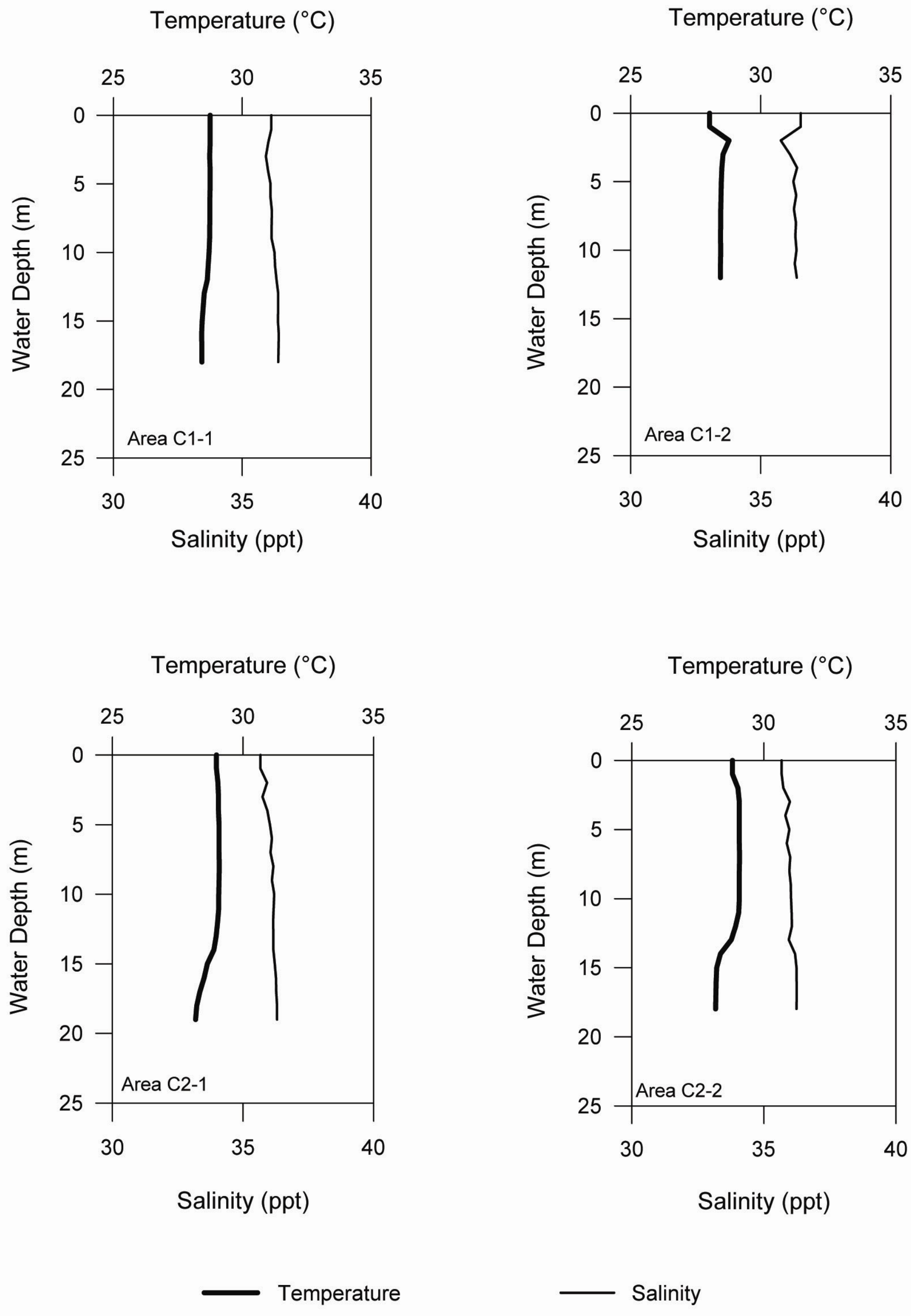

Figure 6-9. Temperature and salinity profiles recorded during September 2000 in Sand Resource Areas C1 and C2.

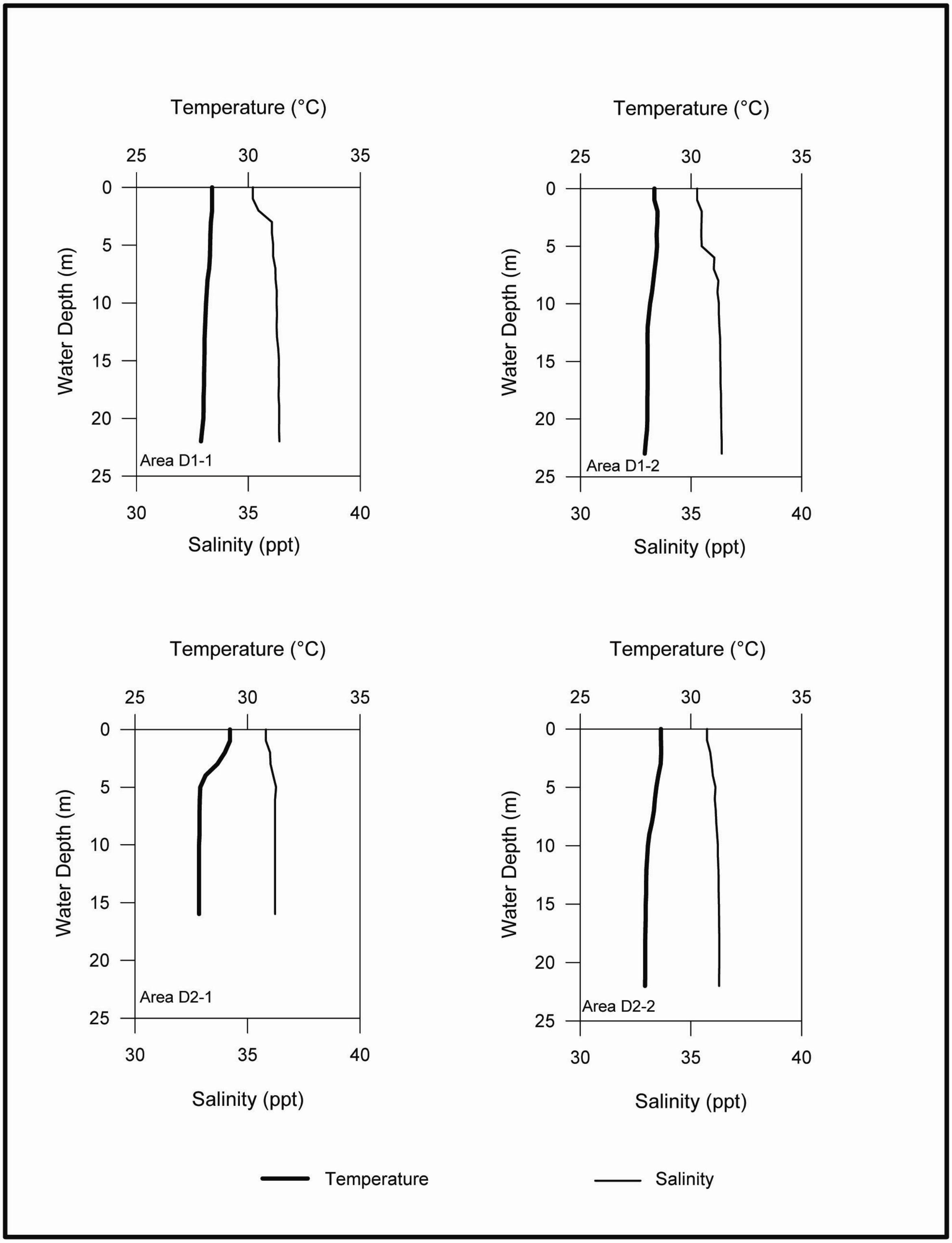

Figure 6-10. Temperature and salinity profiles recorded during September 2000 in Sand Resource Areas D1 and D2.

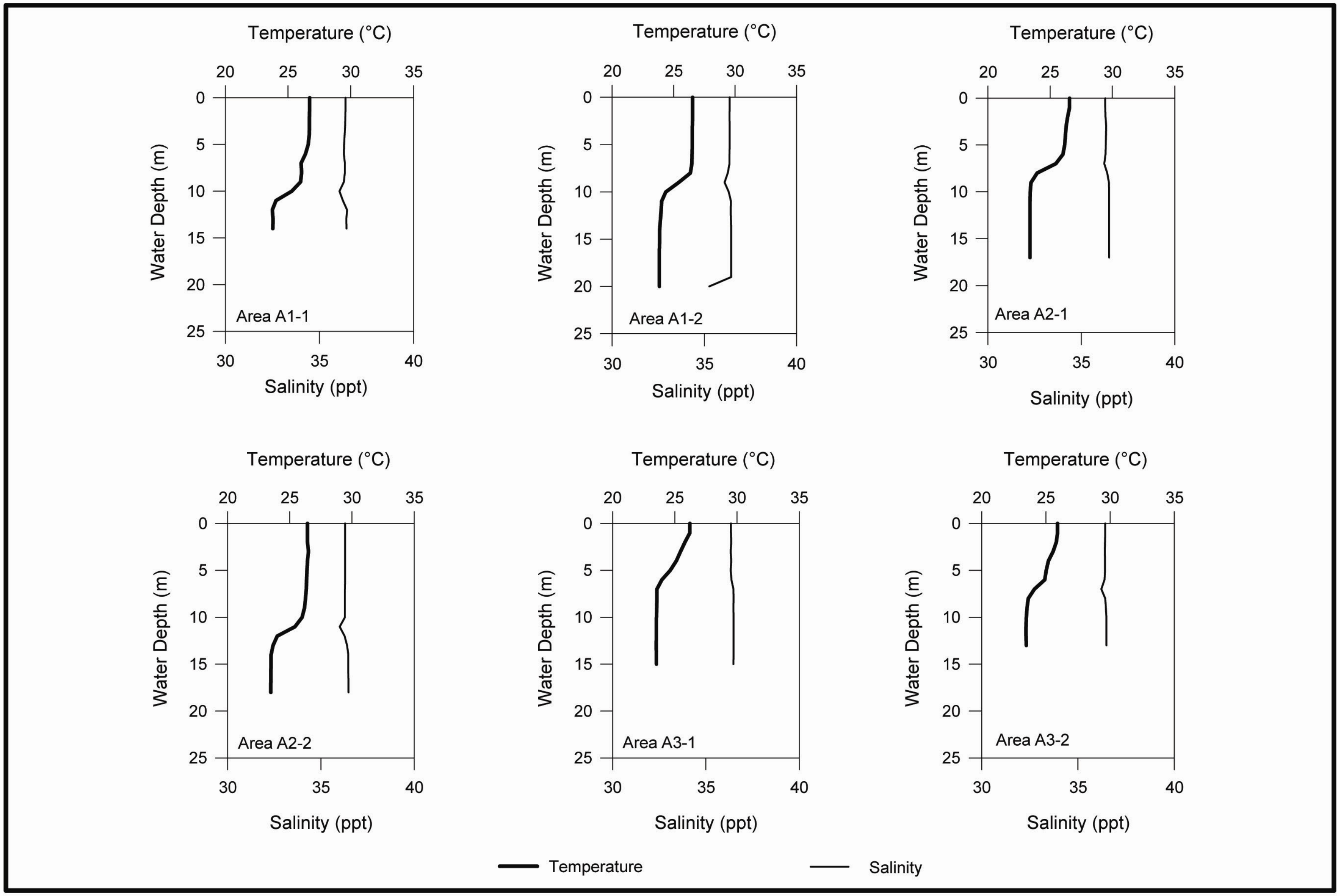

Figure 6-11. Temperature and salinity profiles recorded during June 2001 in Sand Resource Areas A1, A2, and A3.

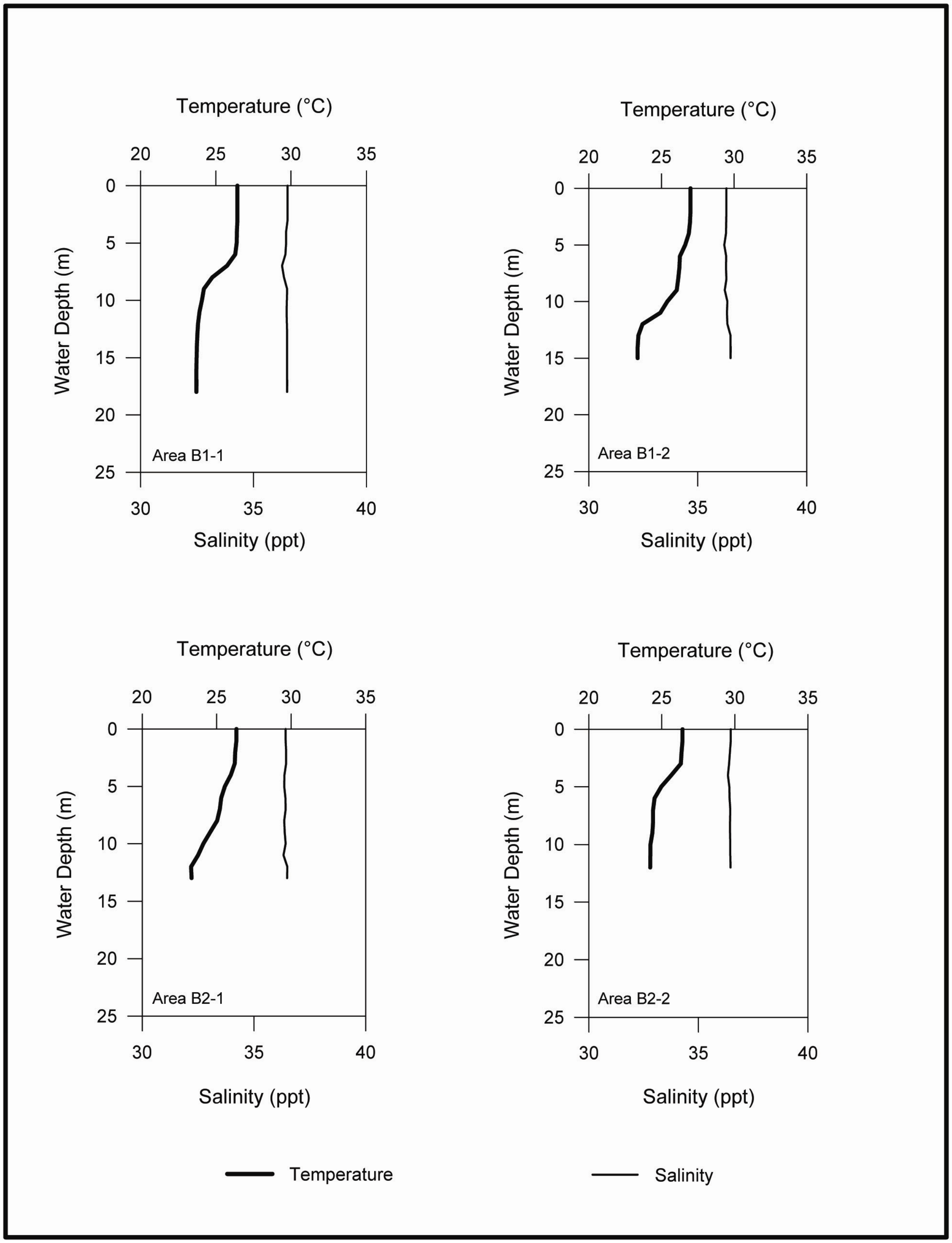

Figure 6-12. Temperature and salinity profiles recorded during June 2001 in Sand Resource Areas B1 and B2.

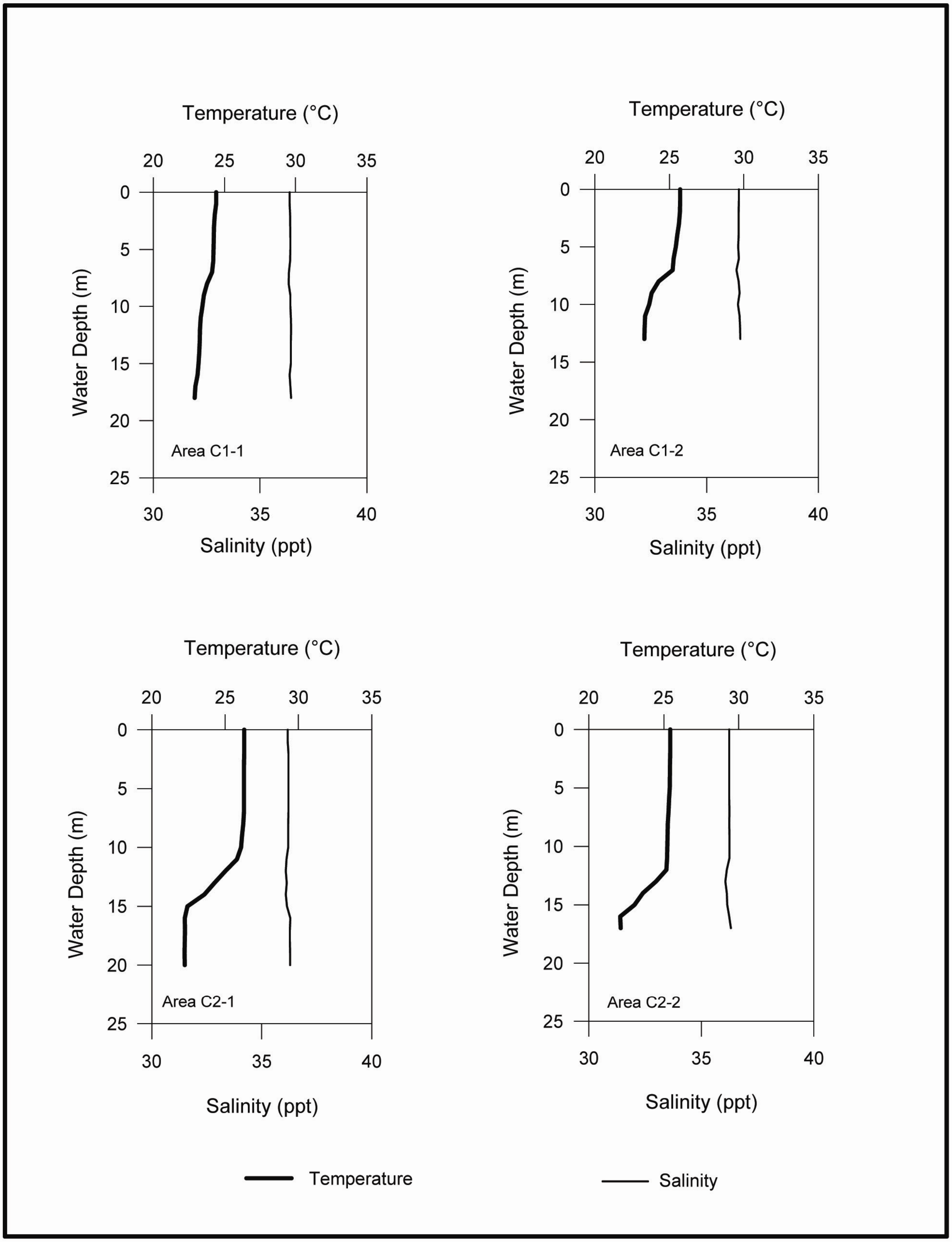

Figure 6-13. Temperature and salinity profiles recorded during June 2001 in Sand Resource Areas C1 and C2.

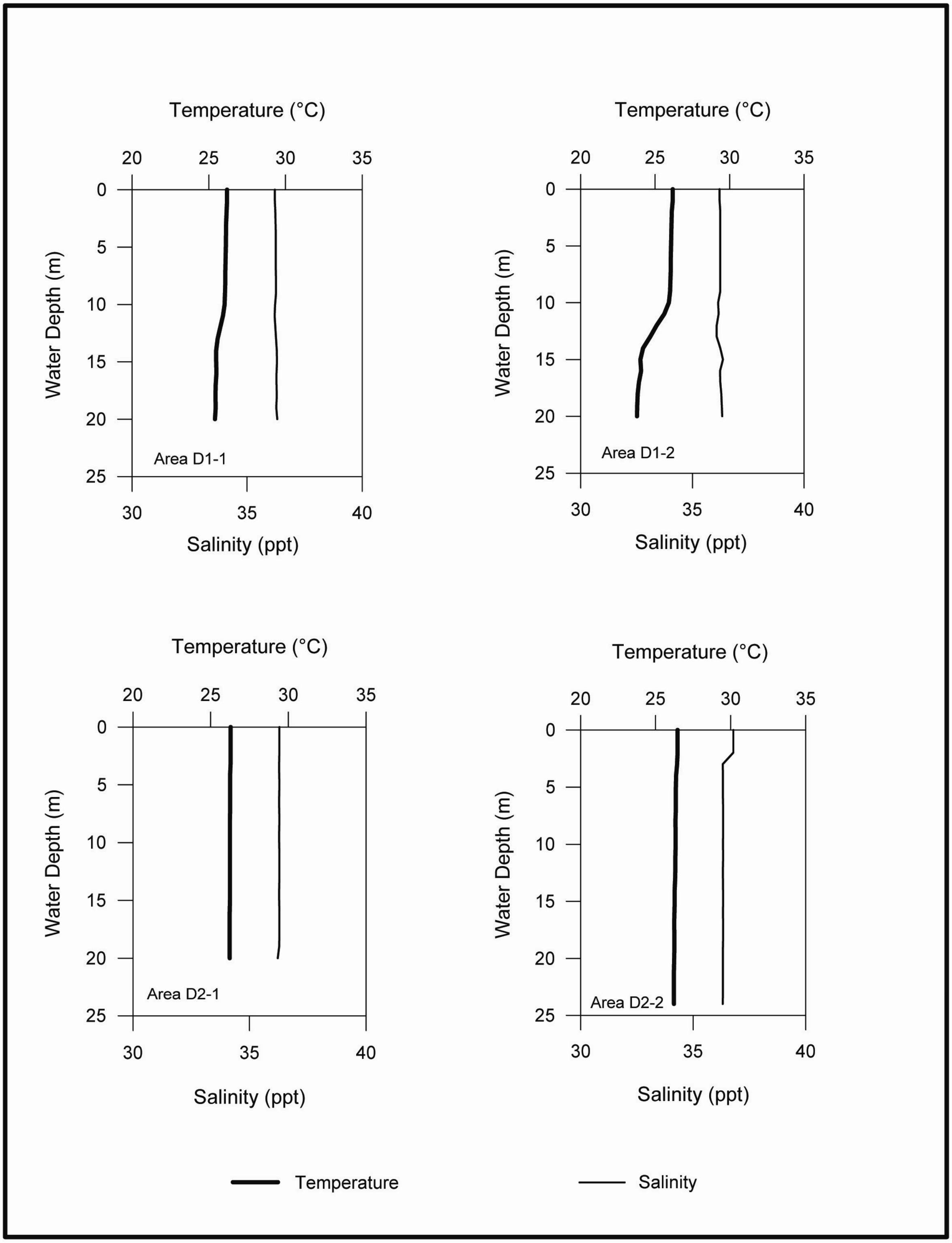

Figure 6-14. Temperature and salinity profiles recorded during June 2001 in Sand Resource Areas D1 and D2.

Table 6-3. Sediment type summary for September 2000 Survey 1 and June 2001 Survey 2 in the nine sand resource areas and seven adjacent stations offshore central east Florida.

Sand Resource Area (A1, B1, C1, D1, etc.) and Adjacent Station (R1, R2, etc.)	Survey	Total No. of Samples Collected	No. of Samples with Particular Sediment Types Based on Folk's Classifications						
			Gravel	Sandy Gravel	Gravelly Sand	Slightly Gravelly Sand	Slightly Gravelly Muddy Sand	Sand	Muddy Sand
A1	1	13						9	4
	2	13				5	1	4	3
A2	1	15						6	9
	2	15					5	6	4
A3	1	3			1			2	
	2	3			1	1		1	
B1	1	28		11	12	3		2	
	2	27	1	12	10	3		1	
B2	1	7			5			2	
	2	7			5	2			
C1	1	24			9	3		11	1
	2	24			10	10	1	3	
C2	1	5			1	1		3	
	2	5			1	2		2	
D1	1	5						4	1
	2	5						4	1
D2	1	4				1		3	
	2	4				1		3	
R1	1	1			1				
	2	1			1				
R2	1	1							1
	2	1							1
R3	1	1		1					
	2	1		1					
R4	1	1			1				
	2	1			1				
R5	1	1			1				
	2	1			1				
R6	1	1						1	
	2	1						1	
R7	1	1			1				
	2	1			1				
Total No. of Samples		221	1	25	63	32	7	68	25

During September, samples from the northernmost areas (A1, A2, and A3) were predominantly sand or muddy sand following Folk's classification. In Area A1, most (9 of 13) samples were classified as sand with the remainder classified as muddy sand. Samples from Area A2 were either muddy sand (9 of 15) or sand (6), and samples from Area A3 yielded 2 described as sand and 1 described as gravelly sand. In Area B1, most samples were either gravelly sand (12 of 28) or sandy gravel (11). Only 2 samples from this area were classified as sand, and the remaining 3 samples were slightly gravelly sand. Most (5 of 7) Area B2 samples were classified as gravelly sand, while the remaining 2 were sand. In Area C1, 11 of 24 samples were sand, 9 were gravelly sand, 3 were slightly gravelly sand, and 1 was muddy sand. In Area C2, 3 of 5 samples were sand, whereas the remaining 2 samples were gravelly sand and slightly gravelly sand. Four of 5 samples from Area D1 were sand and the fifth sample was muddy sand. In Area D2, 3 of 4 samples were sand and the remaining sample was slightly gravelly sand.

Grab samples from the June survey were more variable with respect to Folk's classification than samples from the September survey. Sediment types from June that did not occur during September were gravel (1 sample) and slightly gravelly muddy sand (7 samples). Of 13 samples collected in Area A1, 5 were classified as slightly gravelly sand, 4 as sand, 3 as muddy sand, and 1 as slightly gravelly muddy sand. In Area A2, of 15 samples collected, 6 were sand, 5 were slightly gravelly muddy sand, and 4 were muddy sand. Area A3 had 3 samples, including 1 classified as sand, 1 as gravelly sand, and 1 as slightly gravelly sand. Area B1 yielded 12 of 27 samples classified as sandy gravel and 10 classified as gravelly sand. Remaining samples from Area B1 were slightly gravelly sand (3 samples), gravel (1 sample), and sand (1 sample). In Area B2, samples were either gravelly sand (5 of 7) or slightly gravelly sand (2). Area C1 samples were classified mostly as gravelly sand (10 of 24) or slightly gravelly sand (10). The other 4 samples from Area C1 were classified as sand (3 samples) or slightly gravelly muddy sand (1 sample). The 5 samples collected in Area C2 were sand (2 samples), slightly gravelly sand (2 samples), and gravelly sand (1 sample). In Area D1, 4 of 5 samples were sand, and the remaining sample was muddy sand. In Area D2, 3 of 4 samples were sand, with the fourth sample designated slightly gravelly sand.

Unlike sand resource area stations, all samples taken from a particular adjacent station had the same sediment type during both surveys. Sediment type from adjacent stations only occasionally reflected the major sediment type from the nearest sand resource area.

6.3.3 Soft Bottom

6.3.3.1 Infauna

A phylogenetic list of infauna collected in bottom grabs during the September 2000 and June 2001 surveys is presented in Appendix Table F3-1. A total of 11,757 individuals was collected during the surveys, representing 420 taxa in 13 separate phyla. Infauna were more abundant during September, when grabs yielded an average of 117 individuals, whereas 69 individuals were collected per grab during June. One hundred and eighty-nine taxa (45% of total) were common to both surveys. Of those taxa found in just one of the two surveys, 66% (152 taxa) were sampled during September.

The polychaete *Goniadides carolinae* was numerically dominant, particularly during September, and represented 6.2% of all infauna censused during both surveys.

Other than *G. carolinae*, taxa among the top 10 numerical dominants during both the September and June surveys were the bivalve *Crassinella lunulata*, unidentified rhynchocoels, and the polychaete *Exogone lourei*. Polychaetes and bivalves contributed most to overall abundance, although amphipods were a conspicuous infaunal component at sand bottom stations.

Table 6-4 lists numerically dominant infaunal taxa sampled from each sand resource area during September. Overall, numerically dominant taxa included the polychaete *Mediomastus* (4.57% of all collected individuals), bivalve *Crassinella lunulata* (3.9%), polychaete *G. carolinae* (3.7%), and unidentified ophiuroids (2.9%). The 10 most abundant taxa comprised 27.5% of all infaunal individuals during September. Numerically dominant taxa collected during June are listed in Table 6-5 and included *G. carolinae* (10.4% of all individuals collected), *C. lunulata* (7.0%), and unidentified tubificid oligochaetes (4.7%). The 10 most abundant taxa comprised 37.5% of all infaunal individuals during June.

Table 6-6 presents summary statistics for each sand resource area and combined adjacent stations for the September and June surveys. Values are provided for number of taxa, number of individuals, density, species diversity, evenness, and richness.

The highest mean number of infaunal taxa per station occurred in Area B1 (50 taxa) during September and in Areas B1 (33), C2 (32), and C1 (31) in June. Areas A1 and D1 yielded the lowest mean number of taxa per station during both September (19 and 21, respectively) and June (13 and 14, respectively). Mean number of taxa for combined adjacent stations during September was greater than mean values in the sand resource areas, except for Area B1. Mean number of taxa for combined adjacent stations during June was comparable to the sand resource areas.

Highest infaunal densities (individuals/m^2) were from Area B1 (station average = 4,875) in September and Areas B1 (2,443) and C1 (2,294) during June. Lowest mean densities were from Area D1 (1,083) in September and Area D2 (767) during June. Mean infaunal density for the combined adjacent stations (3,543) in September was greater than densities in the sand resource areas, except for Area B1. Mean infaunal density for combined adjacent stations (1,793) during June was comparable to average densities in the sand resource areas.

Mean values of species diversity (H') and evenness (J') were similar for September and June. Mean values of species richness (D) were greater in September as compared to June ($F = 4.24$, $p<0.05$).

During September, highest mean values of species diversity and richness were found at Area B1 stations (3.26 and 9.31, respectively), and highest mean evenness was found in Areas A3 and C2 (0.92). Area A1 had the lowest mean values of species diversity, evenness, and richness during September (2.34, 0.82, and 4.47, respectively). Stations in Areas C2 and B1 yielded the highest mean values of species diversity (2.99 and 2.98, respectively) during June. Area A2 had the highest mean value of evenness (0.92) and Area C2 had the highest mean richness (7.16) during June. Areas D1 and A1 yielded the lowest mean values of species diversity (2.15 and 2.16, respectively) and richness (3.50 and 3.56, respectively) during June, and lowest mean evenness was in Areas A3 and D1 (0.82).

Table 6-4. Ten most abundant taxa by individual sand resource area and combined adjacent stations (R) for September 2000 Survey 1 offshore central east Florida.

Area	Taxonomic Name	Count	Area	Taxonomic Name	Count
A1	*Crassinella lunulata*	48	C1	*Caecum cooperi*	134
	Bivalvia (LPIL)	44		*Crassinella lunulata*	113
	Metharpinia floridana	39		*Crassinella martinicensis*	86
	Tanaissus psammophilus	26		*Protodorvillea kefersteini*	81
	Echinoidea (LPIL)	24		*Tellina* (LPIL)	74
	Magelona sp. H	20		*Goniadides carolinae*	73
	Goneplacidae (LPIL)	16		*Chione cancellata*	62
	Semelidae (LPIL)	13		*Mediomastus* (LPIL)	60
	Protohaustorius sp. B	10		Arcidae (LPIL)	49
	Acanthohaustorius pansus	9		*Ceratonereis mirabilis*	24
A2	*Lucina radians*	116	C2	*Ceratonereis mirabilis*	23
	Tellinidae (LPIL)	80		*Mediomastus* (LPIL)	17
	Scoletoma verrilli	63		*Armandia maculata*	16
	Magelona sp. H	32		*Protodorvillea kefersteini*	15
	Tellina (LPIL)	24		Glyceridae (LPIL)	10
	Sipuncula (LPIL)	22		*Nephtys simoni*	10
	Goniada littorea	20		Nereididae (LPIL)	8
	Sabellaria vulgaris	18		*Aspidosiphon* (LPIL)	7
	Cerithiidae (LPIL)	16		*Caecum cooperi*	7
	Dentalium texasianum	16		*Goniadides carolinae*	7
A3	Glyceridae (LPIL)	22	D1	*Nereis succinea*	14
	Aspidosiphon albus	15		*Goniada littorea*	10
	Goniadides carolinae	10		*Atys sandersoni*	9
	Caecum johnsoni	7		Tubificidae (LPIL)	9
	Acanthohaustorius intermedius	6		*Mediomastus* (LPIL)	8
	Mediomastus (LPIL)	6		*Prionospio cirrifera*	7
	Metharpinia floridana	5		*Eudevenopus honduranus*	4
	Notomastus americanus	4		*Lucina multilineata*	4
	Owenia fusiformis	4		*Xenanthura brevitelson*	4
	Paraprionospio pinnata	4		*Armandia agilis*	3
B1	*Mediomastus* (LPIL)	170	D2	*Ceratonereis mirabilis*	16
	Ophiuroidea (LPIL)	121		*Atys sandersoni*	14
	Exogone lourei	111		*Armandia maculata*	10
	Goniadides carolinae	104		*Tellina* (LPIL)	10
	Sphaerosyllis piriferopsis	102		*Caulleriella* (LPIL)	9
	Crassinella lunulata	101		*Crassinella lunulata*	8
	Eunice unifrons	96		*Lembos setosus*	7
	Parapionosyllis longicirrata	82		*Aspidosiphon* (LPIL)	6
	Rhynchocoela (LPIL)	80		*Lucina radians*	6
	Pitar fulminatus	78		Arcidae (LPIL)	5
B2	Ophiuroidea (LPIL)	52	R	*Mediomastus* (LPIL)	62
	Goniadides carolinae	25		*Goniadides carolinae*	52
	Sipuncula (LPIL)	24		*Tellina versicolor*	49
	Dentatisyllis carolinae	23		*Anadara transversa*	45
	Anadara ovalis	16		*Caecum johnsoni*	39
	Branchiostoma (LPIL)	14		Rhynchocoela (LPIL)	29
	Rhynchocoela (LPIL)	13		*Lucina radians*	27
	Crassinella martinicensis	11		*Armandia maculata*	22
	Tubificidae (LPIL)	10		*Opisthodonta* sp. B	21
	Filogranula sp. A	9		*Maera caroliniana*	20

LPIL = Lowest practical identification level.

Table 6-5. Ten most abundant taxa by individual sand resource area and combined adjacent stations (R) for June 2001 Survey 2 offshore central east Florida.

Area	Taxonomic Name	Count	Area	Taxonomic Name	Count
A1	*Crassinella lunulata*	49	B2	*Goniadides carolinae*	60
	Metharpinia floridana	19		Tubificidae (LPIL)	49
	Bathyporeia parkeri	16		*Syllis ortizi*	16
	Rhynchocoela (LPIL)	11		*Glycera* (LPIL)	14
	Acanthohaustorius millsi	7		Sipuncula (LPIL)	12
	Bivalvia (LPIL)	6		Oligochaeta (LPIL)	11
	Protohaustorius wigleyi	6		*Crassinella lunulata*	10
	Tubificidae (LPIL)	6		*Aspidosiphon* (LPIL)	8
	Acanthohaustorius shoemakeri	5		*Limopsis cristata*	8
	Echinoidea (LPIL)	5		*Tanaissus psammophilus*	7
	Lucina multilineata	17		*Crassinella lunulata*	153
A2	*Ervilia concentrica*	13	C1	*Goniadides carolinae*	74
	Acanthohaustorius intermedius	11		Tubificidae (LPIL)	59
	Bivalvia (LPIL)	9		Sipuncula (LPIL)	50
	Tellina (LPIL)	9		Maldanidae (LPIL)	42
	Echinoidea (LPIL)	8		*Protodorvillea kefersteini*	42
	Magelona sp. H	8		*Syllis ortizi*	42
	Metharpinia floridana	6		*Metharpinia floridana*	39
	Mitrella lunata	6		*Armandia maculata*	33
	Rhynchocoela (LPIL)	6		*Caecum imbricatum*	30
	Goniadides carolinae	40		*Goniadides carolinae*	18
A3	*Prionospio cristata*	26	C2	Tubificidae (LPIL)	13
	Acanthohaustorius intermedius	21		Terebellidae (LPIL)	11
	Aspidosiphon (LPIL)	14		*Syllis ortizi*	10
	Crassinella lunulata	11		*Dissodactylus* (LPIL)	7
	Metharpinia floridana	9		*Odontosyllis enopla*	7
	Rhynchocoela (LPIL)	8		Ophiuroidea (LPIL)	7
	Acteocina candei	5		*Crassinella lunulata*	6
	Balanoglossus (LPIL)	5		*Glycera* (LPIL)	6
	Caecum johnsoni	5		*Tellina* (LPIL)	6
	Goniadides carolinae	206		*Eudevenopus honduranus*	19
B1	*Exogone lourei*	65	D1	Tellinidae (LPIL)	16
	Crassinella lunulata	58		*Ophelina acuminata*	14
	Tubificidae (LPIL)	54		*Goniada littorea*	11
	Caecum johnsoni	47		*Armandia maculata*	9
	Glycera (LPIL)	44		*Cyclaspis varians*	7
	Maera caroliniana	43		*Lucina multilineata*	5
	Bhawania heteroseta	38		Rhynchocoela (LPIL)	5
	Syllis ortizi	34		*Bathyporeia parkeri*	4
	Mediomastus (LPIL)	33		*Armandia agilis*	3
	Tellinidae (LPIL)	10		*Goniadides carolinae*	50
D2	*Goniada littorea*	8	R	*Atrina seminuda*	44
	Goniadides carolinae	7		*Mediomastus* (LPIL)	19
	Synelmis ewingi	6		Cirratulidae (LPIL)	18
	Aspidosiphon muelleri	4		Tubificidae (LPIL)	18
	Caecum imbricatum	4		*Crassinella lunulata*	16
	Metharpinia floridana	4		Sipuncula (LPIL)	14
	Aspidosiphon (LPIL)	3		Maldanidae (LPIL)	13
	Bathyporeia parkeri	3		*Glycera* (LPIL)	12
	Branchiostoma (LPIL)	3		*Maera caroliniana*	11

LPIL = Lowest practical identification level.

Table 6-6. Summary of infaunal statistics for September 2000 Survey 1 and June 2001 Survey 2 in each sand resource area and combined adjacent stations (R) offshore central east Florida.

Area	No. of Stations (n)	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
September 2000													
A1	7	19	8.25	57	40	1,421	1,009	2.34	0.35	0.82	0.07	4.47	1.42
A2	7	31	9.52	107	21	2,679	513	2.84	0.47	0.83	0.07	6.46	1.82
A3	3	24	5.13	54	38	1,342	941	2.92	0.09	0.92	0.08	6.06	0.37
B1	14	50	19.19	195	119	4,875	2,964	3.26	0.38	0.85	0.07	9.31	2.62
B2	4	29	7.87	84	38	2,088	941	2.86	0.22	0.85	0.01	6.39	1.25
C1	12	36	9.39	120	72	2,998	1,797	2.96	0.28	0.84	0.06	7.37	1.41
C2	3	33	18.58	89	66	2,233	1,650	3.06	0.55	0.92	0.06	7.32	2.78
D1	3	21	10.15	43	28	1,083	711	2.63	0.52	0.88	0.07	5.30	1.85
D2	3	28	9.64	63	43	1,575	1,064	3.00	0.24	0.91	0.05	6.62	1.36
R	7	43	20.39	142	94	3,543	2,351	3.12	0.58	0.85	0.09	8.54	3.08
June 2001													
A1	7	13	4.68	32	13	800	327	2.16	0.50	0.85	0.11	3.56	1.12
A2	7	21	1.86	34	8	861	195	2.84	0.18	0.94	0.04	5.67	0.63
A3	3	18	1.15	66	47	1,642	1,176	2.38	0.19	0.82	0.08	4.37	0.53
B1	1	33	9.42	98	59	2,443	1,474	2.98	0.28	0.87	0.05	7.07	1.37
B2	4	28	8.04	78	36	1,938	905	2.81	0.30	0.85	0.04	6.25	1.35
C1	12	31	9.27	92	42	2,294	1,048	2.88	0.37	0.86	0.06	6.60	1.61
C2	3	32	17.90	71	53	1,775	1,331	2.99	0.66	0.90	0.00	7.16	3.13
D1	3	14	2.52	39	11	983	277	2.15	0.43	0.82	0.11	3.50	0.87
D2	3	16	3.46	31	10	767	260	2.51	0.13	0.91	0.05	4.40	0.58
R	7	27	13.90	72	62	1,793	1,557	2.83	0.42	0.91	0.06	6.20	2.03

Cluster Analysis

Patterns of infaunal similarity among stations were examined with cluster analysis. Cluster analysis excluded those taxa that were rare in samples or that were redundant (i.e., had an LPIL designation except for *Mediomastis* [LPIL] and *Tellina* [LPIL]). Most taxa included in the cluster analysis were polychaetes (42 taxa), followed by bivalves (17), various crustaceans (8), and gastropods (7).

When examined over both surveys, normal cluster analysis produced five groups (Groups A through E) of stations (samples) that were similar with respect to species composition and relative abundance. Station Groups B and C mostly included the same stations; Station Group C (33 stations) was composed exclusively of September samples, and Group B (39 stations) had mostly June samples. Groups A (23 stations), E (27 stations), and D (4 stations) included samples from both September and June.

Group A stations yielded high numbers of certain taxa that were relatively rare at other stations, including the burrowing amphipods *Acanthohaustorius intermedius*, *Bathyporeia parkeri*, and *Metharpinia floridana*. Overall, Group A stations were relatively depauperate. Sediments were sand at 75% of Group A stations, with remaining stations containing slightly gravelly sand. Station Groups B and C included stations with measurable gravel and yielded the greatest numbers of overall numerical dominants, particularly the bivalves *Chione cancellata*, *Crassinella lunulata*, *Crassinella martinicensis*, and *Tellina* (LPIL), gastropod *Caecum cooperi*, and polychaetes *Goniadides carolinae*, *Mediomastus* (LPIL), *Protodorvillea kefersteini*, and *Sphaerosyllis piriferopsis*. Certain Group C (September) stations yielded several taxa that were rare or absent in other station groups, including the bivalves *Anomia simplex* and *Pitar fulminatus*, gastropod *Calyptraea centralis*, and polychaetes *Dentatisyllis carolinae*, *Eunice unifrons, Exogone dispar, Mediomastus californiensis*, *Parapionosyllis longicirrata*, and *Sabellaria vulgaris*. Group D included four stations with variable sediments that were relatively depauperate, but did contain relatively high numbers of taxa that were otherwise rare in samples, including the bivalve *Atrina seminuda,* gastropod *Atys sandersoni*, and polychaete *Nereis succinea*. Group E included muddy sand and pure sand stations that yielded taxa that were rare or absent at other stations, especially at stations with measurable gravel. Taxa collected primarily from muddy sand Group E stations included the bivalve *Lucina radians* and polychaetes *Magelona* sp. H, *Paraprionospio pinnata*, and *Scoletoma verrilli*. Group E stations with pure sand were relatively depauperate but did yield sand taxa such as the amphipod *Eudevenopus honduranus* and polychaete *Armandia agilis*.

Figure 6-15 shows the spatial distribution of stations grouped by normal analysis of infaunal data. Station Group A mostly included stations in Areas A1, A2, and A3 and also included a few stations from the southern portion of the study area. Station Groups B and C mostly included stations in the central part of the study area, primarily Areas B1, B2, C1, and C2. Group D stations were located at the southernmost portion of the study area (Areas D1, D2, and Adjacent Station 7). Group E stations were scattered throughout the study area, but were most concentrated in Area A2.

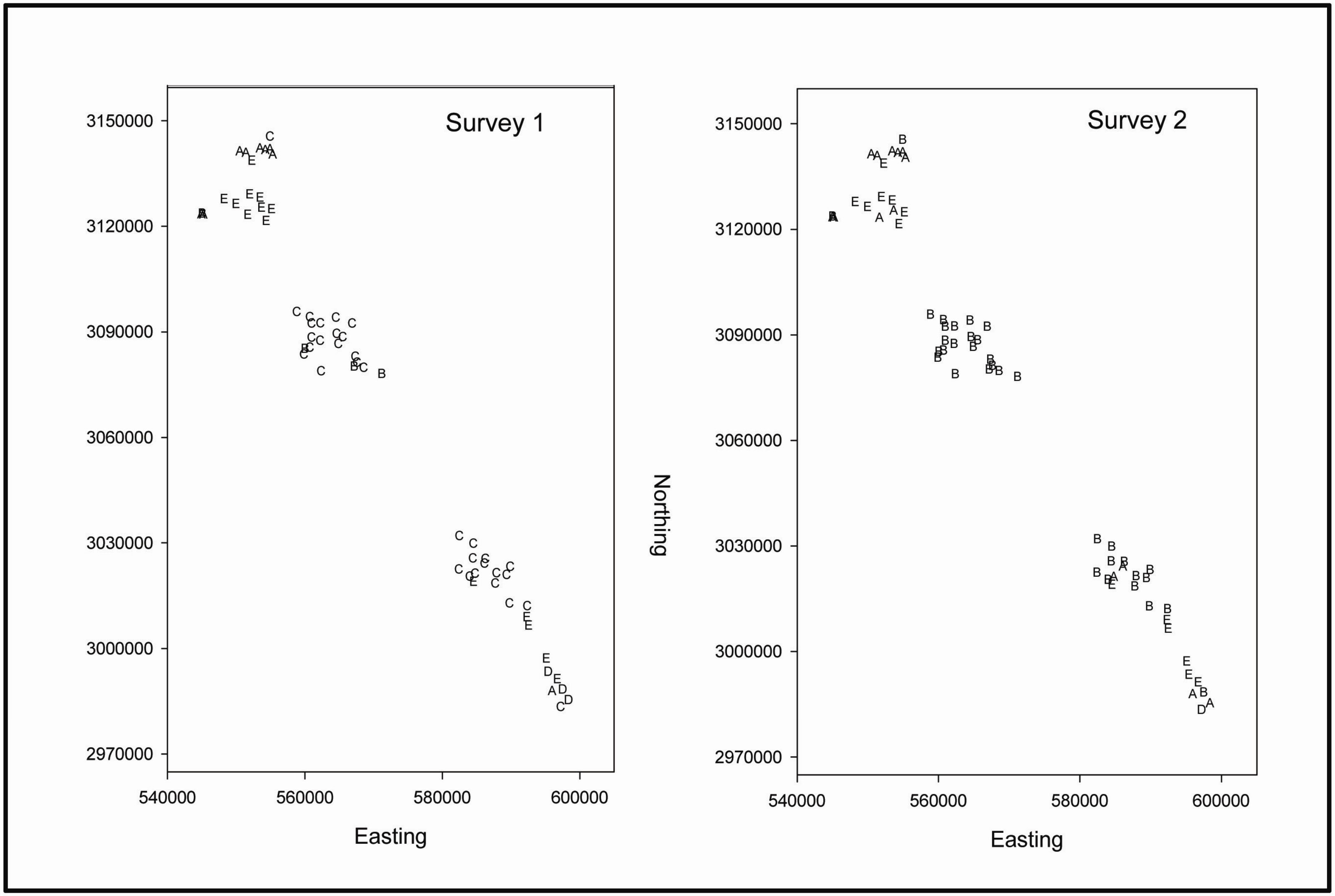

Figure 6-15. Station groups (A to E) based on normal cluster analysis of infaunal samples collected during September 2000 Survey 1 and June 2001 Survey 2 in the nine sand resource areas and adjacent stations offshore central east Florida.

Inverse cluster analysis examining both the September and June surveys resulted in four groups of taxa (Groups 1 through 4) that reflected their co-occurrence in sand resource area samples (Table 6-7). Many infauna included in the overall cluster analysis were relatively rare and heterogeneously distributed across sand resource area stations, and these taxa were not included in the four species groups clearly defined by the inverse analysis.

Table 6-7. Infaunal species groups resolved from inverse cluster analysis of all samples collected during the September 2000 Survey 1 and June 2001 Survey 2 in the nine sand resource areas and adjacent stations offshore central east Florida.

GROUP 1
- *Goniadides carolinae*
- *Crassinella lunulata*
- *Protodorvillea kefersteini*
- *Caecum cooperi*
- *Chione cancellata*
- *Crassinella martinicensis*
- *Anadara ovalis*
- *Ervilia concentrica*
- *Hemipodus roseus*
- *Owenia fusiformis*
- *Podarke obscura*
- *Axiothella* sp. A
- *Ceratonereis mirabilis*
- *Magelona pettiboneae*
- *Heteropodarke formalis*
- *Arene tricarinata*
- *Aonides mayaguezensis*
- *Isolda pulchella*

GROUP 2
- *Metharpinia floridana*
- *Acanthohaustorius intermedius*
- *Acteocina candei*
- *Goniada littorea*
- *Eudevenopus honduranus*
- *Armandia agilis*
- *Lucina multilineata*
- *Bathyporeia parkeri*

GROUP 3
- *Lucina radians*
- *Scoletoma verrilli*
- *Magelona* sp. H
- *Dentalium texasianum*
- *Paraprionospio pinnata*
- *Semele proficua*

GROUP 4
- *Exogone lourei*
- *Caecum johnsoni*
- *Sphaerosyllis piriferopsis*
- *Dentatisyllis carolinae*
- *Maera caroliniana*
- *Bhawania goodei*
- *Bhawania heteroseta*
- *Mediomastus californiensis*
- *Sabellaria vulgaris*
- *Eunice unifrons*
- *Pitar fulminatus*
- *Parapionosyllis longicirrata*
- *Exogone dispar*
- *Anomia simplex*
- *Calyptraea centralis*
- *Nereis riisei*
- *Anadara transversa*
- *Chione grus*
- *Kupellonura* sp. A
- *Opisthodonta* sp. B
- *Eumida sanguinea*

Species Group 1 included taxa collected from stations with measurable gravel, located primarily in Areas B1, B2, and C1. The most abundant taxa in Group 1 included the bivalves *Chione cancellata*, *Crassinella lunulata*, and *Crassinella martinicensis*, gastropod *Caecum cooperi*, and polychaetes *Goniadides carolinae* and *Protodorvillea kefersteini*. Group 2 taxa were most abundant at sand stations and at a few stations with measurable mud, particularly in Areas A1 and A2, and included the amphipods *Acanthohaustorius* *intermedius*, *Bathyporeia parkeri*, *Eudevenopus honduranus*, and *Metharpinia floridana* and polychaetes *Armandia agilis* and *Goniada littorea*. Species Group 3 included taxa predominantly from muddy sand stations, and included the bivalves *Lucina radians* and *Semele proficua*, polychaetes *Magelona* sp. H, *Paraprionospio pinnata*, and *Scoletoma verrilli*, and scaphopod *Dentalium texasianum*. Species Group 4 included taxa abundant at stations with gravel bottoms, particularly in Area B1 during September, and included the amphipod *Maera caroliniana*, bivalves *Anomia simplex* and *Pitar fulminatus*, gastropods *Caecum johnsoni* and *Calyptraea centralis*, and polychaetes *Dentatisyllis carolinae*, *Eunice unifrons*, *Exogone lourei*, *Parapionosyllis longicirrata*, and *Sphaerosyllis piriferopsis*.

Adjacent stations in the central portion of the study area (R2, R3, R4, and R5) had sediments and infauna similar to stations in their adjacent sand resource areas. Normal analysis therefore grouped these adjacent stations with stations in their adjacent areas. Those adjacent stations with sediment different from most stations in their respective adjacent areas (R1, R6, and R7) yielded different infaunal assemblages, placing these stations in different groups from those in their adjacent sand resource areas.

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 axes 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 the amount of silt in the benthic grabs (-0.8040) and to a lesser degree with the amount of clay (-0.6479) and station depth (-0.6460). The second canonical variate (CAN2) best correlated with survey/month (0.7803).

6.3.3.2 Soft Bottom Epifauna

Trawl samples yielded a total of 32 taxa and 510 individuals of epifauna. September trawls yielded 329 epifaunal individuals in 25 taxa (Table 6-8), and 90% of these individuals were collected from Areas A1, A2, and A3. The most numerous species collected during September were the mantis shrimp (*Squilla empusa*), swimming crabs *Portunus gibbesii* and *P. spinimanus*, unidentified squids, white shrimp (*Litopenaeus setiferus*), longnose spider crab (*Libinia dubia*), blue crab (*Callinectes sapidus*), and calico box crab (*Hepatus epheliticus*). These eight taxa collectively accounted for 89% of the total epifaunal catch during September.

June trawls yielded 181 epifaunal individuals in 16 taxa (Table 6-9). The most abundant taxa collected during this survey were the sand dollars *Encope michelini* and *Mellita isometra*, longnose spider crab (*Libinia dubia*), and calico scallop (*Argopecten gibbus*). These four taxa collectively accounted for 86%, with the sand dollars from Area B2 contributing 60%, of the total epifaunal catch during June. Except for *E. michelini* and longnose spider crab, which were collected from multiple stations, epifaunal taxa were heterogeneously distributed during June.

Table 6-8. Epifauna and demersal fishes collected by mongoose trawl during the September 2000 Survey 1 of the nine sand resource areas offshore central east Florida.

Taxa	A1		A2		A3		B1		B2		C1		C2		D1		D2		Total
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	
Invertebrates																			
Squilla empusa	32	17	35	18	9	1		1											113
Portunus gibbesii		9	5	5	7	3	1				2				1	1			34
Squid		13		13	2	6													34
Litopenaeus setiferus	11	15	3					4											33
Libinia dubia	16	1	4	1		1													23
Portunus spinimanus		10	3		6	1	1	1	1										23
Callinectes sapidus	8	8	1	1															18
Hepatus epheliticus	12		3			1													16
Argopecten gibbus					1	1		4											6
Renilla sp.	3	1		1		1													6
Mellita isometra												3							3
Podochela sp.																		3	3
Alpheidae			2																2
Cronius ruber								1								1			2
Iliacantha sp.	2																		2
Sicyonia sp.			1			1													2
Aplysia sp.																		1	1
Bryozoa		1																	1
Calappa flammea								1											1
Calappa gallus																1			1
Encope michelini																	1		1
Hypselodoris webbi																	1		1
Luidia senegalensis						1													1
Lytechinus variegatus																1			1
Majidae																	1		1
Fishes																			
Anchoa lyolepis	1			10	60	50	50	500	50		58	2			39	52			872
Cynoscion nothus	125	38	15	16	7	5													206
Centropristis philadelphica	8	24	7	2	12	7		1											61
Stellifer lanceolatus	16	12	5	3	1	5													42
Micropogonias undulatus		16			4	3		3						10		1			37
Selene setipinnis	19	6		1	2	2		3							1				34
Trichiurus lepturus				1				2					21	5		1			30
Prionotus scitulus	1			1	18	5		2											27
Prionotus rubio	11	3	4	1	1														20
Eucinostomus gula					6	9		1											16
Menticirrhus americanus	6	2	5	1				1											15
Etropus crossotus	7	1	3	1			1												13
Sphyraena borealis		1	1	3	1	1	1						4						12
Selene vomer		7							1										8
Harengula clupeola	2		1	2					1										6
Monacanthus hispidus	1				1			1	1								1	1	6
Sardinella aurita											6								6
Anchoa hepsetus	2		3																5
Bothus robinsi															4		1		5
Citharichthys sp.															5				5
Citharichthys spilopterus	1	3			1														5
Larimus fasciatus	3	1			1														5
Opisthonema oglinum	1			2		1							1						5
Arius felis	1	2														1			4
Citharichthys macrops		3			1														4
Narcine brasiliensis	1	2						1											4
Scorpaena		3	1																4
Sphyrna tiburo								4											4
Acanthostracion quadricornis																3			3
Eucinostomus argenteus							2									1			3
Chloroscombrus chrysurus			1	1															2
Cryptotomus roseus																1	1		2
Diplectrum bivittatum					2														2
Diplectrum formosum		1					1												2
Ogcocephalus radiatus		1														1			2
Scomberomorus cavalla				1							1								2
Aluterus monoceros																	1		1
Bairdiella chrysoura																1			1
Chaetodipterus faber							1												1
Chilomycterus schoepfi																1			1
Cynoscion regalis																1			1
Echeneis naucrates																1			1
Gymnura mircrura		1																	1
Haemulon aurolineatum																1			1
Harengula jaguana															1				1
Hippocampus erectus						1													1
Lutjanus synagris						1													1
Ophidion sp.								1											1
Orthopristis chrysoptera								1											1
Rachycentron canadum																1			1
Symphurus diomedianus								1											1
Syngnathus louisianae							1												1
Synodus foetens						1													1
Invertebrate Totals																			
Total Individuals	84	75	57	39	25	17	2	12	1	0	2	3	0	0	1	4	3	4	329
Total Taxa	7	9	9	6	5	10	2	6	1	0	1	1	0	0	1	4	3	2	25
Fish Totals																			
Total Individuals	206	127	46	46	118	91	57	522	53	0	65	2	26	15	50	67	4	1	1,496
Total Taxa	17	19	11	15	15	13	7	14	4	0	3	1	3	2	5	14	4	1	53
Fish and Invertebrate Totals																			
Grand Total Individuals	290	202	103	85	143	108	59	534	54	0	67	5	26	15	51	71	7	5	1,825
Grand Total Taxa	24	28	20	21	20	23	9	20	5	0	4	2	3	2	6	18	7	3	78

Table 6-9. Epifauna and demersal fishes collected by mongoose trawl during the June 2001 Survey 2 of the nine sand resource areas offshore central east Florida.

Species	A1		A2		A3		B1		B2		C1		C2		D1		D2		Total
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	
Invertebrates																			
Encope michelini									35	31			2		2			4	74
Mellita isometra									18	25									43
Libinia dubia	5		3	7		6		1											22
Argopecten gibbus		2					15												17
Podochela sp.								1	1	5									7
Arca zebra						3				1									4
Luidia senegalensis	3																		3
Portunus gibbesii																		2	2
Portunus sp.	1														1				2
Holothuria sp.														1					1
Luidia clathrata								1											1
Lytechinus variegatus								1											1
Octopus sp.													1						1
Ophioderma sp.								1											1
Squilla empusa			1																1
Sicyonia sp.	1																		1
Fishes																			
Synodus foetens	2		9	1	4	3													19
Bothus ocellatus																	5		5
Bothus robinsi							1			1							1	2	5
Trachinocephalus myops																		5	5
Sphoeroides spengleri																4			4
Cryptotomus roseus																3			3
Etropus crossotus					1	2													3
Prionotus scitulus							1	2											3
Canthigaster rostrata																2			2
Citharichthys spilopterus																	1	1	2
Diplectrum formosum							1	1											2
Monacanthus hispidus																2			2
Acanthostracion quadricornis																1			1
Aluterus scriptus						1													1
Centropristis philadelphica		1																	1
Chaetodon sedentarius																1			1
Citharichthys macrops	1																		1
Hemipteronotus novacula									1										1
Prionotus sp.	1																		1
Sparisoma sp.																1			1
Synodus sp.															1				1
Invertebrate Totals																			
Total Individuals	11	4	5	9	1	11	16	7	55	64	1	2	4	3	4	2	1	8	181
Total Taxa	5	2	3	2	1	3	2	6	4	5	1	1	3	2	3	1	1	3	16
Fish Totals																			
Total Individuals	4	1	9	1	5	6	3	3	1	1	0	0	0	0	1	14	7	8	64
Total Taxa	3	1	1	1	2	3	3	2	1	1	0	0	0	0	1	7	3	3	21
Fish and Invertebrate Totals																			
Grand Total Individuals	14	3	13	8	5	15	18	8	55	63	0	0	3	1	4	14	7	14	245
Grand Total Taxa	7	2	3	2	2	5	4	7	4	5	0	0	2	1	3	7	3	5	37

6.3.3.3 Soft Bottom Demersal Fishes

Trawl samples yielded a total of 63 taxa and 1,560 individuals of demersal fishes. September trawls yielded 1,496 fishes in 53 taxa (Table 6-8). The most numerous species were dusky anchovy (*Anchoa lyolepis*), silver seatrout (*Cynoscion nothus*), rock sea bass (*Centropristis philadelphica*), star drum (*Stellifer lanceolatus*), and Atlantic croaker (*Micropogonias undulatus*). These five species collectively accounted for 81% of the total fish catch during September. The largest catches were made in Areas B1, A1, and A3. Trawl catches averaged 83.1 fishes per haul and ranged from 522 individuals in Trawl 2 from Area B1 to 0 individuals in Trawl 2 from Area B2. The total number of fish taxa per trawl ranged from 19 in Trawl 2 from Area A1 to 0 in Trawl 2 from Area B2. The average number of fish taxa per trawl was 2.9. Areas A1 and B1 yielded the highest total numbers of fish taxa during September.

June trawls yielded 64 fishes in 21 taxa (Table 6-9). The most abundant taxa were inshore lizardfish *Synodus foetens*, eyed flounder *Bothus ocellatus*, spottail flounder *Bothus robinsi*, and snakefish *Trachinocephalus myops*. These four species collectively accounted for 53% of the total fish catch during June. Trawl catches averaged 3.6 fishes per haul and ranged from 0 individuals per haul at Areas C1 and C2 to 14 individuals in Trawl 2 from Area D1. The number of taxa per area ranged from 0 in Areas C1 and C2 to 7 in Trawl 2 from Area D1 during June.

Cluster analysis of the sample similarity matrix indicated a clear difference in the species composition between Surveys 1 and 2 (Figure 6-16). Species composition varied from the southernmost areas (D1 and D2) to the northernmost areas (A1, A2, and A3). Species composition and abundance of fishes collected in Areas A and B were fundamentally different than the species composition found in Areas C and D. Species such as silver seatrout *Cynoscion nothus*, Atlantic croaker *Micropogonias undulatus*, banded drum *Larimus fasciatus*, and star drum *Stellifer lanceolatus* were most common in September catches made in Areas A and B. In contrast, southern Areas C and D supported a mixture of species including demersal forms such as lizardfishes, flatfishes, and searobins. In Area D, hard bottom associated fishes, including reef butterflyfish *Chaetodon sedentarius*, bluelip parrotfish *Cryptotomus roseus*, and sharpnose puffer *Canthigaster rostrata*, were among the species caught.

6.3.4 Hard Bottom

Appendix E provides information and figures concerning hard bottom in the sand resource sites and throughout the study area based on existing information. The following two subsections concerning hard bottom epibiota and demersal fishes discuss results and provide figures based on the biological field surveys for this study.

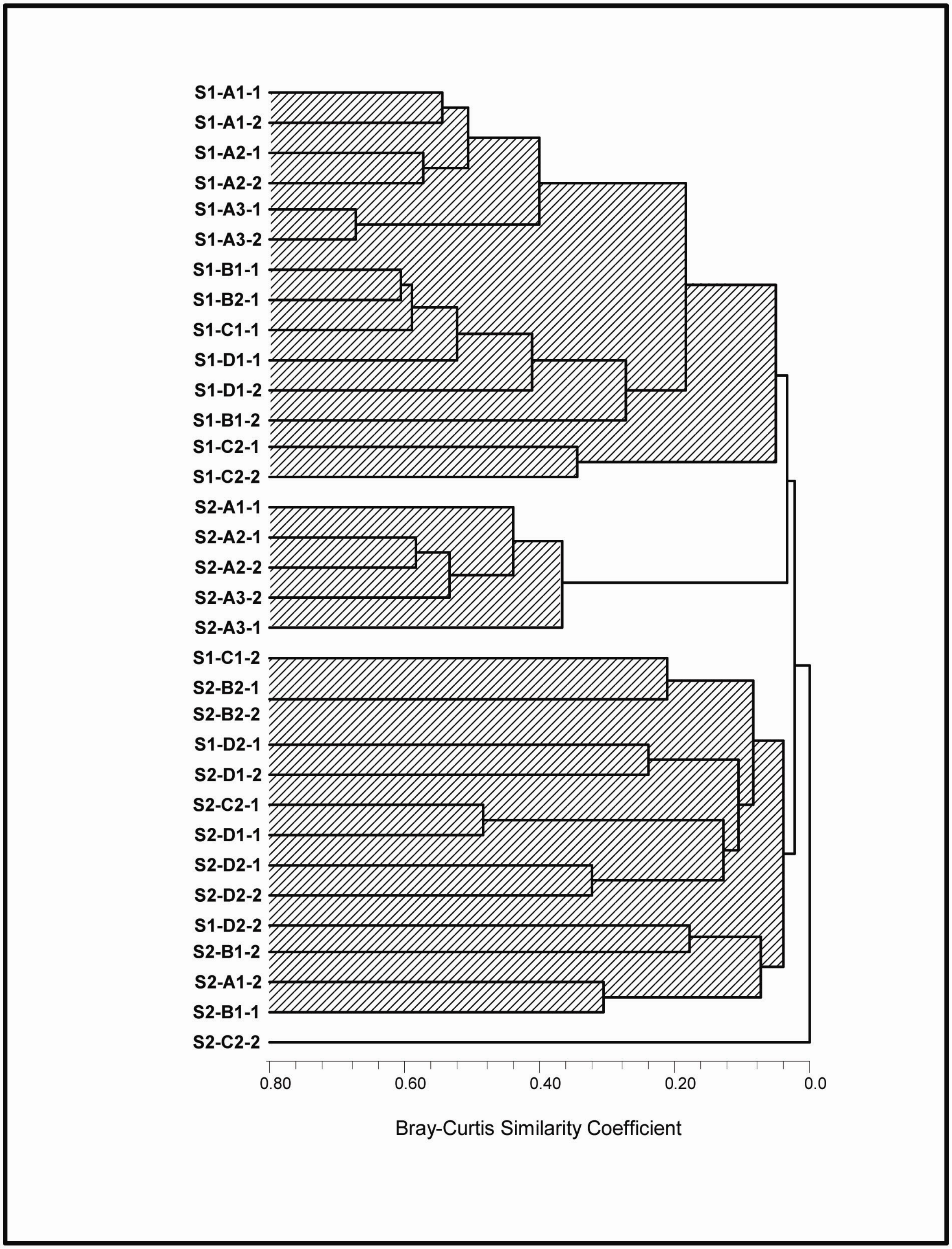

Figure 6-16. Dendrogram of all trawl samples collected for epifauna and demersal fishes during the September 2000 Survey 1 and June 2001 Survey 2 of the nine sand resource areas offshore central east Florida.

6.3.4.1 Hard Bottom Epibiota

The southern hard bottom transect extended from slightly south of Area D2 to slightly east of Area C2 within a depth stratum that averaged 24 m (Figures 6-17 through 6-19). Hard bottom was present discontinuously along much of the transect. Outcrops of varying relief were observed in and around Areas D1 and D2, between Areas D1 and C2, and east of Area C2. Along the transect, 38% was identified as hard bottom and 62% as sand. Although hard bottom profiles ranged from high to low relief along the entire transect, epibiota, particularly octocorals, exhibited a marked south to north trend in density and species composition. Numbers of octocoral taxa and their observed densities decreased with increasing latitude. Table 6-10 lists epibiota observed along the entire transect. Appendix F4 (Photos 1 to 44) provides still images taken along the transect.

Conspicuous epibiota observed along the transect consisted of algae, sponges, octocorals, stony corals, mollusks, and ascideans. In the southern portion of the transect, octocorals (*Iciligorgia schrammi*, *Muricea* spp., *Pseudopterogorgia* spp., and *Swiftia exserta*) were observed on most exposed hard bottom (Appendix F4, Photos 2 to 4). Large sponges including *Ircinia* sp. and *Spheciospongia* sp. also occurred in this area along with calcareous algae (*Halimeda* spp.), hydrozoans, and ascideans (*Eudistoma* sp.). Some stony corals were present but colonies were too small to discern in video and most still photographs (see Appendix F4, Photo 5). Higher relief (1.5 to 2 m) features supported the highest observed densities of octocorals (see Appendix F4, Photos 6 to 10). On the high relief feature south of Area D2, octocorals were large and very dense. Octocoral density and species richness declined in Area D1. In the center of Area D2 (Figure 6-17) there was a transect segment where medium to low relief hard bottom was covered by dense stands of *Sargassum* algae (Appendix F4, Photos 15 and 16). Hard bottom north of Area D1 and in Area D2 was covered with algae, sponges, hydrozoans, ascideans, and sparse octocorals (Appendix F4, Photos 19 to 25). Eventually an algal-sponge assemblage predominated on outcrops, regardless of relief. Near the end of the transect, to the east of Area C2 (Figure 6-19), hard bottom was frequently covered by a layer of sediment (Appendix F4, Photos 35 and 36) and epibiota consisted primarily of algae such as *Dictyota* spp. (Appendix F4, Photo 37). The octocoral *Lophogorgia* sp. was the only conspicuous octocoral observed north of Area D2 (Appendix F4, Photos 39 and 40). Large sponges were occasionally observed along this segment of the transect (Appendix F4, Photo 43).

To characterize hard bottom habitats in the northern study area, eight target sites were chosen in the vicinity of Areas B1 and B2 to perform drift transects with the camera sled (Figure 6-20). Target sites were selected using information obtained from local fishers, researchers (F. Vose, 2002, pers. comm., FMRI), and charts. Hard bottom surveyed along these northern transects ranged from low relief areas totally or partially covered by sediment to medium relief undercut ledges supporting dense epibiotal assemblages. Epibiota observed was composed of species similar to those observed near Area C2 on the southern transect. Algae, sponges, hydrozoans, the octocoral *Lophogorgia* sp., and stony corals were most frequently observed.

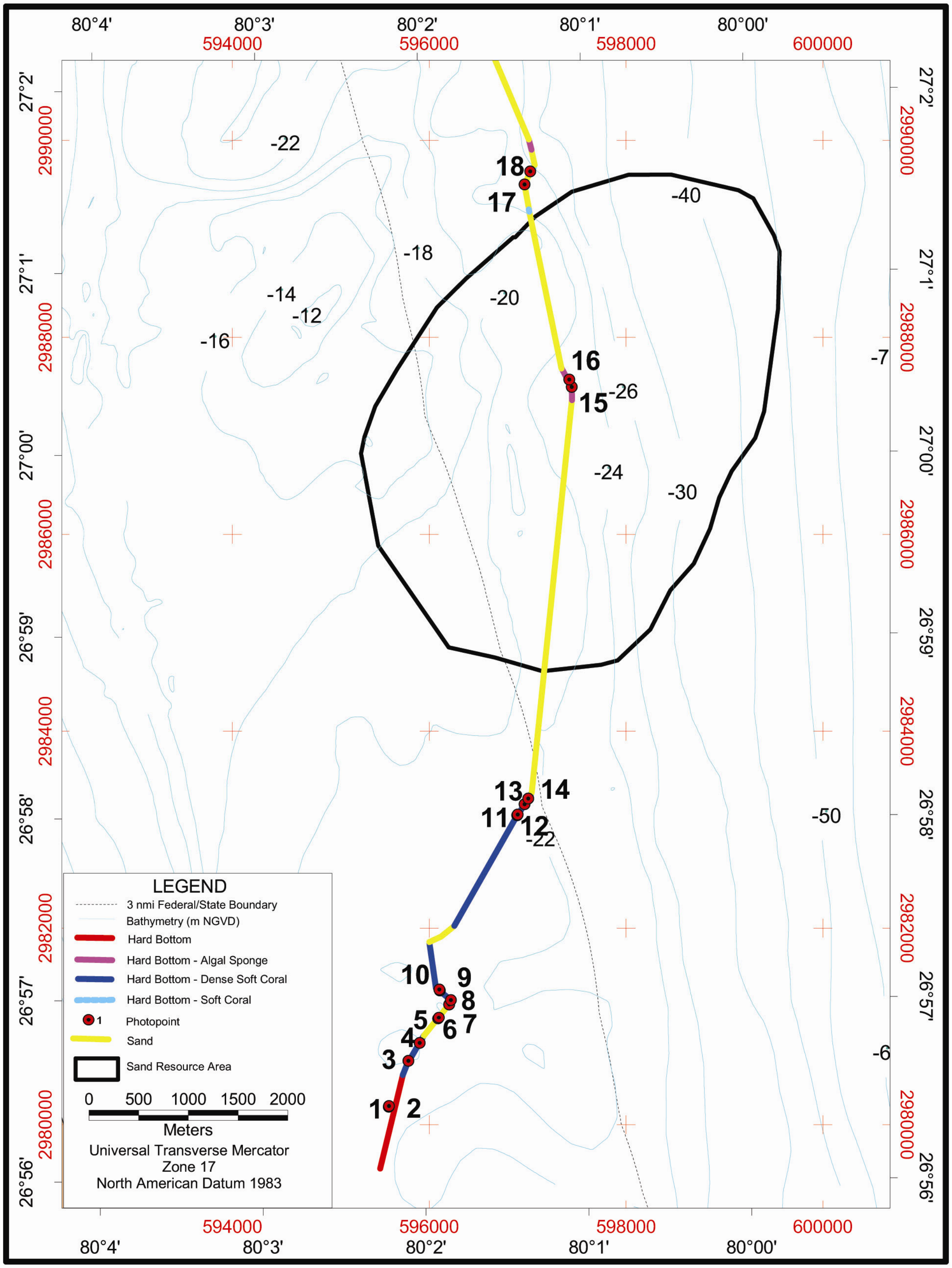

Figure 6-17. Hard bottom video and still photographic transect relative to Sand Resource Area D2.

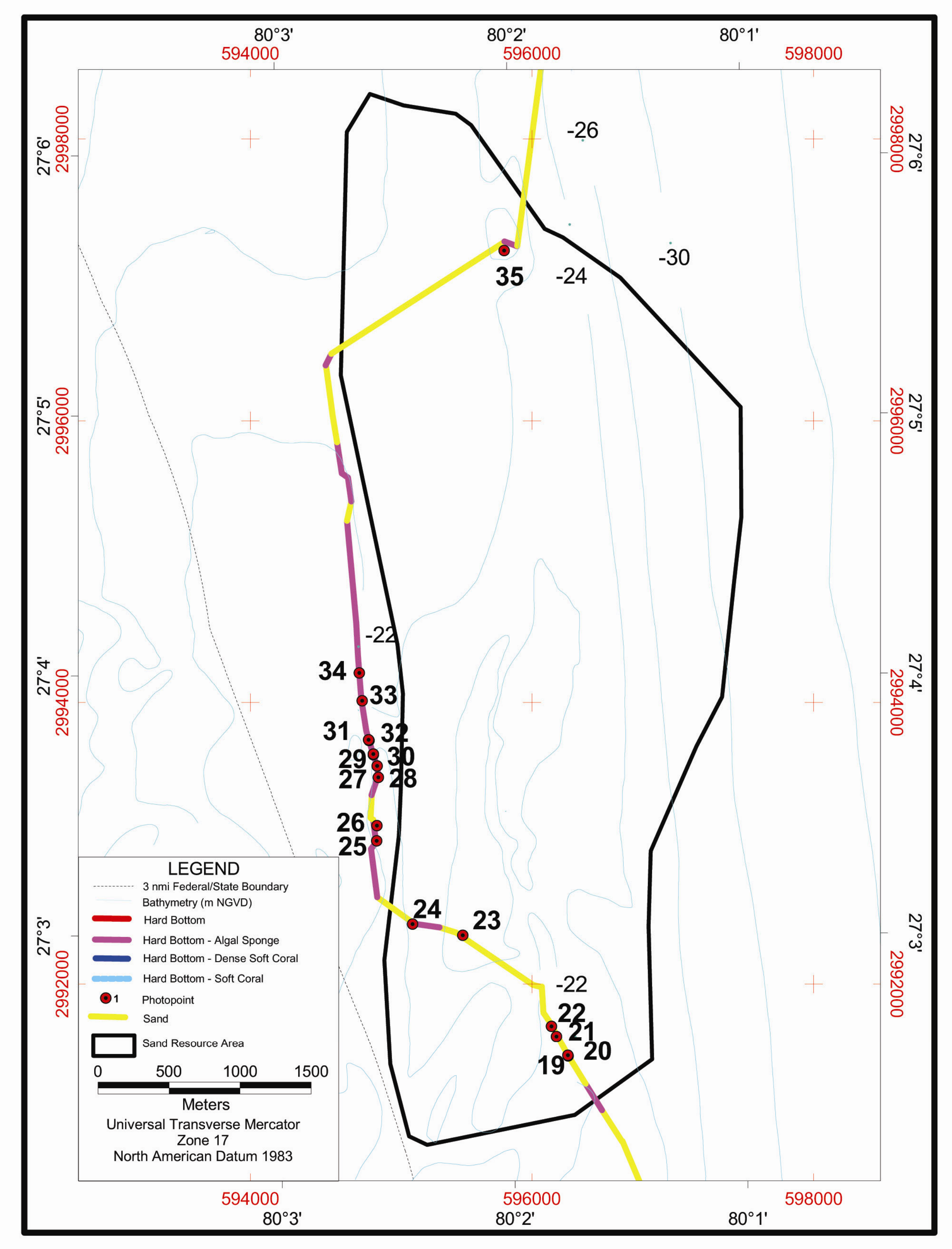

Figure 6-18. Hard bottom video and still photographic transect relative to Sand Resource Area D1.

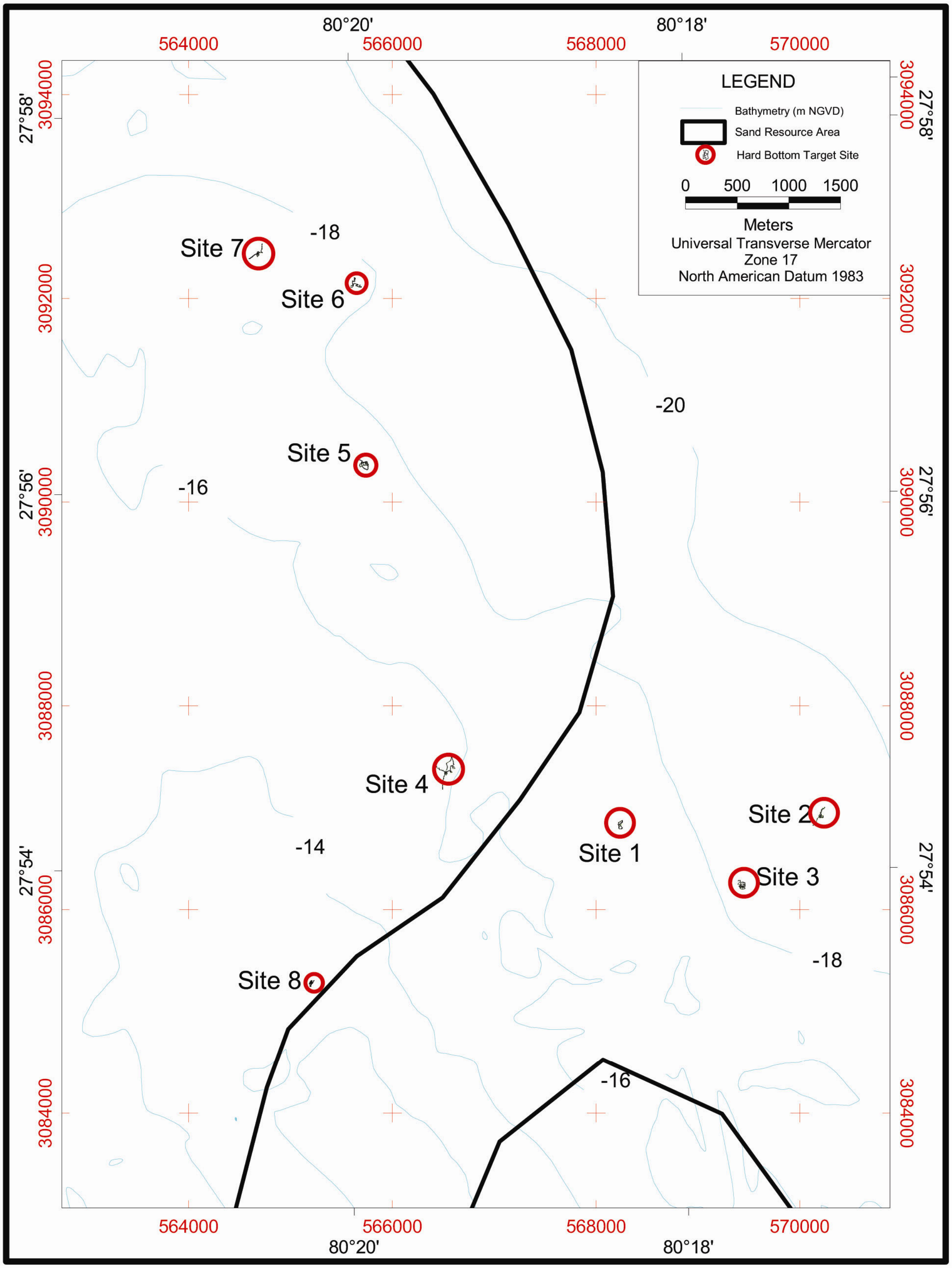

Figure 6-19. Hard bottom video and still photographic transect relative to Sand Resource Area C2.

Table 6-10. Conspicuous epibiota observed in video and still images collected during southern (April 2002) and northern (October 2002) hard bottom surveys.

Group and Taxa	Southern Area	Northern Area
Algae		
Avrainvillea sp.	X	
Caulerpa spp.	X	
Dictyota spp.	X	
Gracilaria spp.	X	X
Halimeda spp.	X	X
Padina sp.		X
Sargassum spp.	X	X
Udotea spp.	X	
Sponges		
Agelas spp.	X	
Cinachyra sp.	X	
Cliona sp.	X	X
Iotrochota birotulata	X	
Ircinia sp.	X	
Niphates sp.	X	
Spheciospongia sp.	X	
Octocorals		
Ellisella sp.	X	
Erythropodium caribaeorum	X	
Eunicea spp.	X	
Iciligorgia schrammi	X	
Lophogorgia sp.	X	X
Muricea spp.	X	
Plexaurella spp.	X	
Pseudoplexaura sp.	X	
Pseudopterogorgia spp.	X	
Pterogorgia citrina	X	
Swiftia exserta	X	
Stony (Scleractinian) Corals		
Eusmilia fastigiata	X	
Oculina varicosa		X
Stephanocoenia intersepts	X	
Hydrozoans		
Dentitheca dentritica	X	
Mollusks		
Cassius madagascarensis	X	
Pinna sp.	X	
Echinoderms	X	
Isostichopus sp.	X	
Ascidians		
Didemnidae	X	X
Eudistoma sp.	X	X

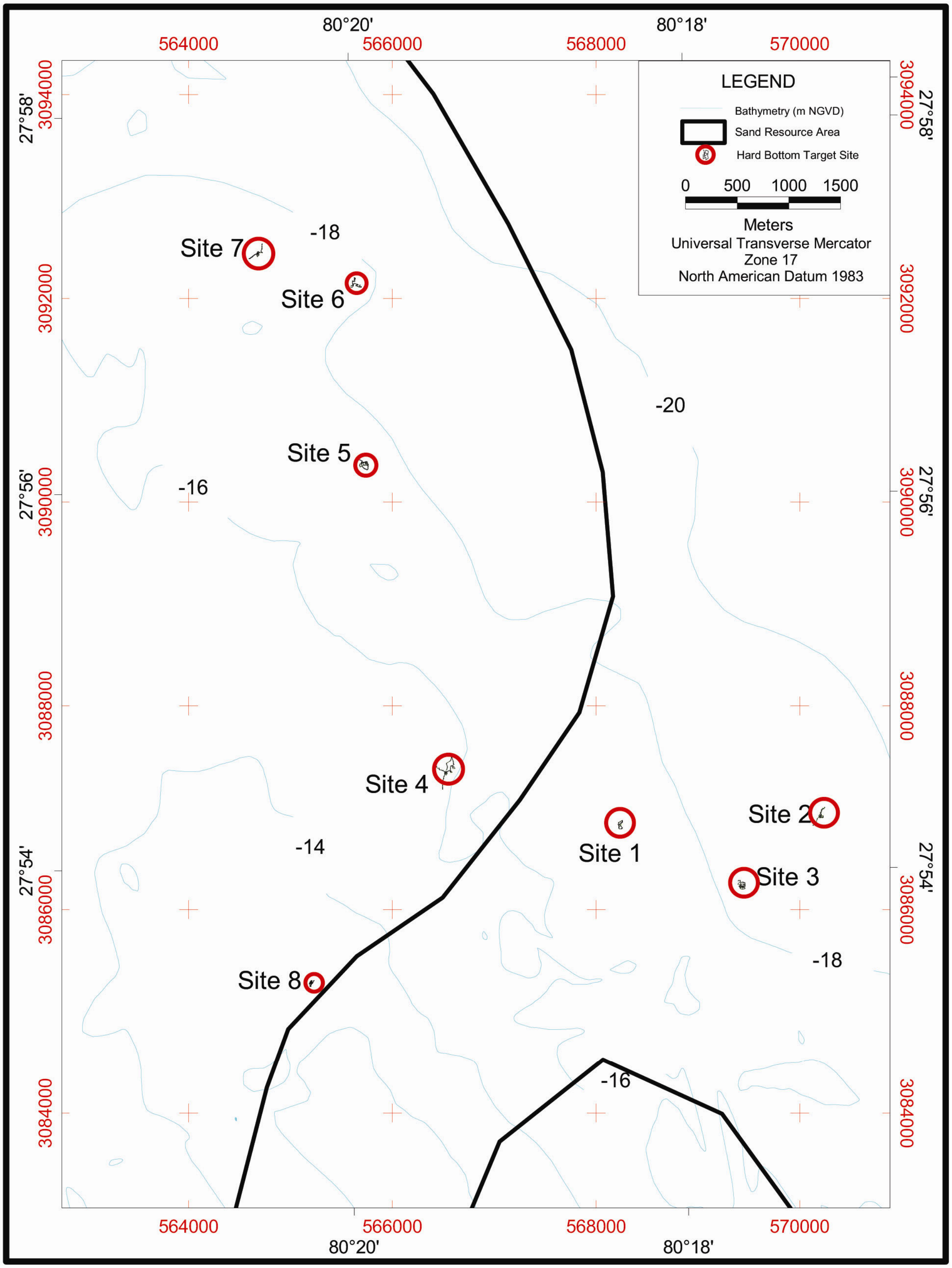

Figure 6-20. Eight hard bottom sites surveyed by video and still cameras relative to Sand Resource Areas B1 and B2.

At Site 1, low and medium relief hard bottom was present (Appendix F4, Photos 45 and 46). Figure 6-21 shows the drift path of the transect, which was mostly hard bottom. Much of the area classified as low relief hard bottom was covered with sand. Hard bottom presence was confirmed by algae, hydrozoans, and octocorals protruding through the sediment veneer along much of this transect. At Site 2 much of the soft bottom between rocky outcrops consisted of very coarse sand and shell hash (Appendix F4, Photo 47). Only a short segment of this transect was classified as hard bottom, and that was partially covered with sand (Figure 6-22; Appendix F4, Photo 48). The camera drift made over Site 3 revealed no hard bottom, only coarse sediment and shell fragments, thus this transect was not shown. Video images from Site 4 revealed hard bottom along much of the transect (Figure 6-23). Hard bottom observed along this transect included medium (Appendix F4, Photo 49) and low relief (Appendix F4, Photos 50, 51, and 52) features. Algae, hydrozoans, octocorals, and sponges were present on the hard bottom. Red and brown algae contributed most to the observed epibiotal cover along this transect.

At Site 5 (Figure 6-24), medium relief hard bottom with an undercut ledge along a portion of its length was present (Appendix F4, Photos 53 and 54). To the north of Site 5, Site 6 (Figure 6-25) also revealed medium relief areas with undercut ledges (Appendix F4, Photo 55). Epibiotal assemblages on hard bottom along this transect ranged from dense stands of algae, hydrozoans, sponges, and stony corals (Appendix F4, Photo 56) to sparse rock (Appendix F4, Photo 57). Site 7 (Figure 6-26) showed medium relief hard bottom ledges and low relief hard bottom on top of the ledges. Algae, sponges, and octocorals also were present at Site 7. The survey of Site 8 did not reveal any hard bottom, only coarse to medium sand with mixed shell fragments. Because there was no hard bottom encountered, the transect from Site 8 was not shown.

6.3.4.2 Hard Bottom Demersal Fishes

Fishes observed during the April 2002 hard bottom survey of the southern area are listed in Table 6-11. Forty-three taxa from 21 families were observed in video or still images along the entire transect. Most fishes recorded were reef-associated forms, with grunts (Haemulidae), seabasses (Serranidae), and wrasses (Labridae) having the highest numbers of species.

Video and still photos from the northern area transects completed during October 2002 yielded 24 fish taxa from 17 families. Most of these taxa also were observed along the southern transect. Some species including sand perch *Diplectrum formosum*, belted sandfish *Serranus subligarius*, twospot cardinalfish *Apogon pseudomaculatus*, and round scad *Decapterus punctatus* were only observed in northern transects.

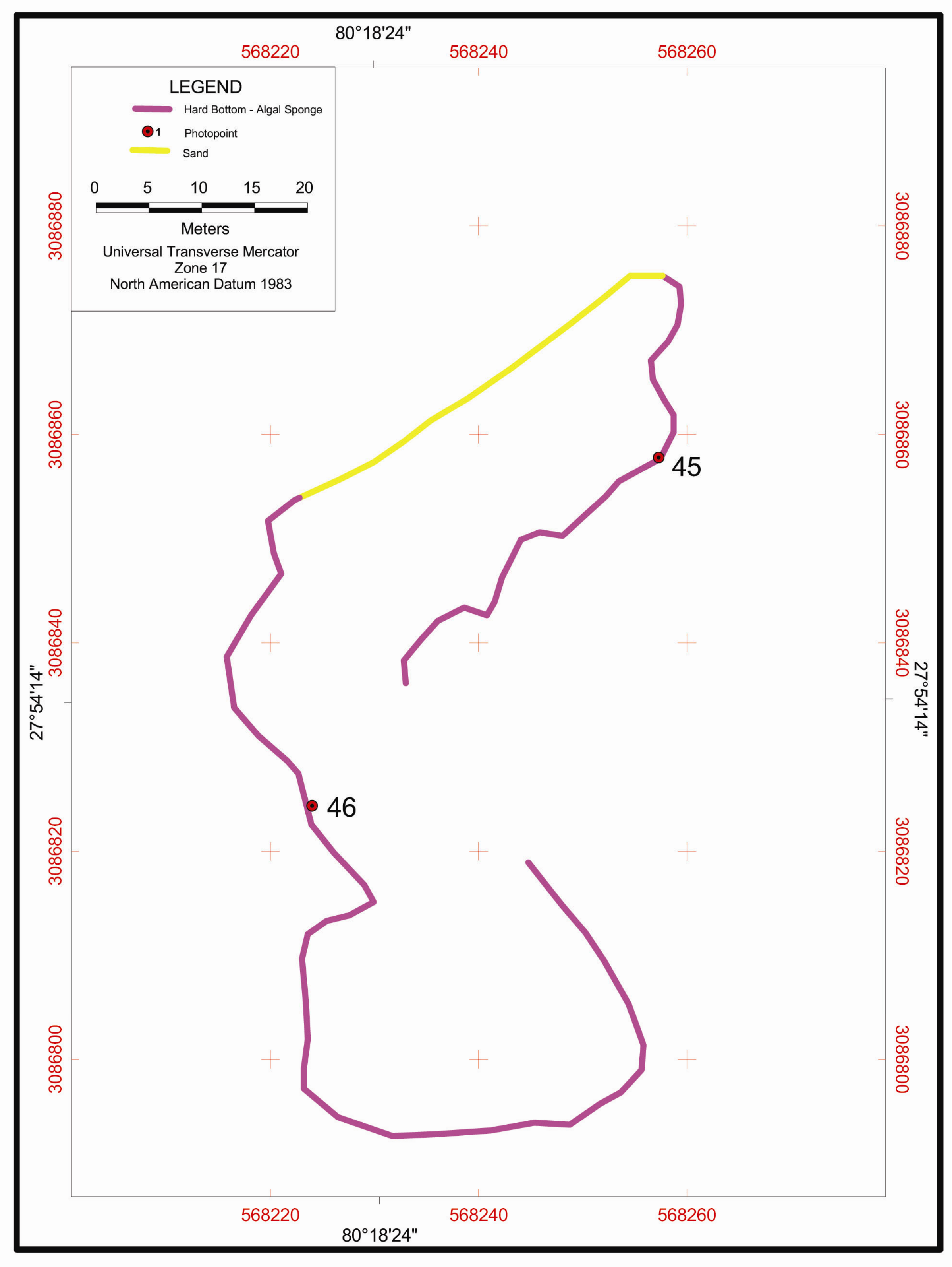

Figure 6-21. Video and still photographic transect surveyed at hard bottom Site 1 during October 2002.

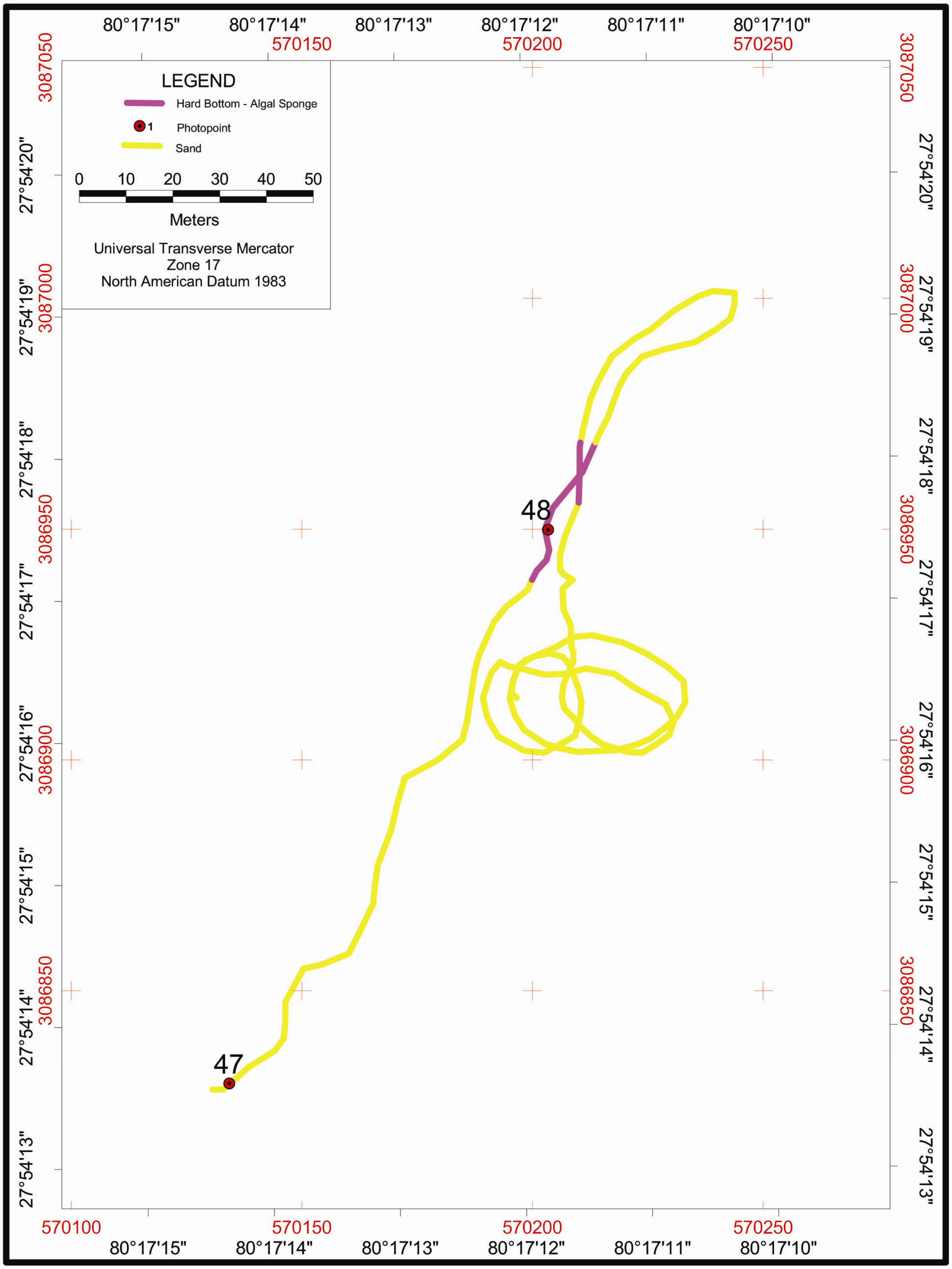

Figure 6-22. Video and still photographic transect surveyed at hard bottom Site 2 during October 2002.

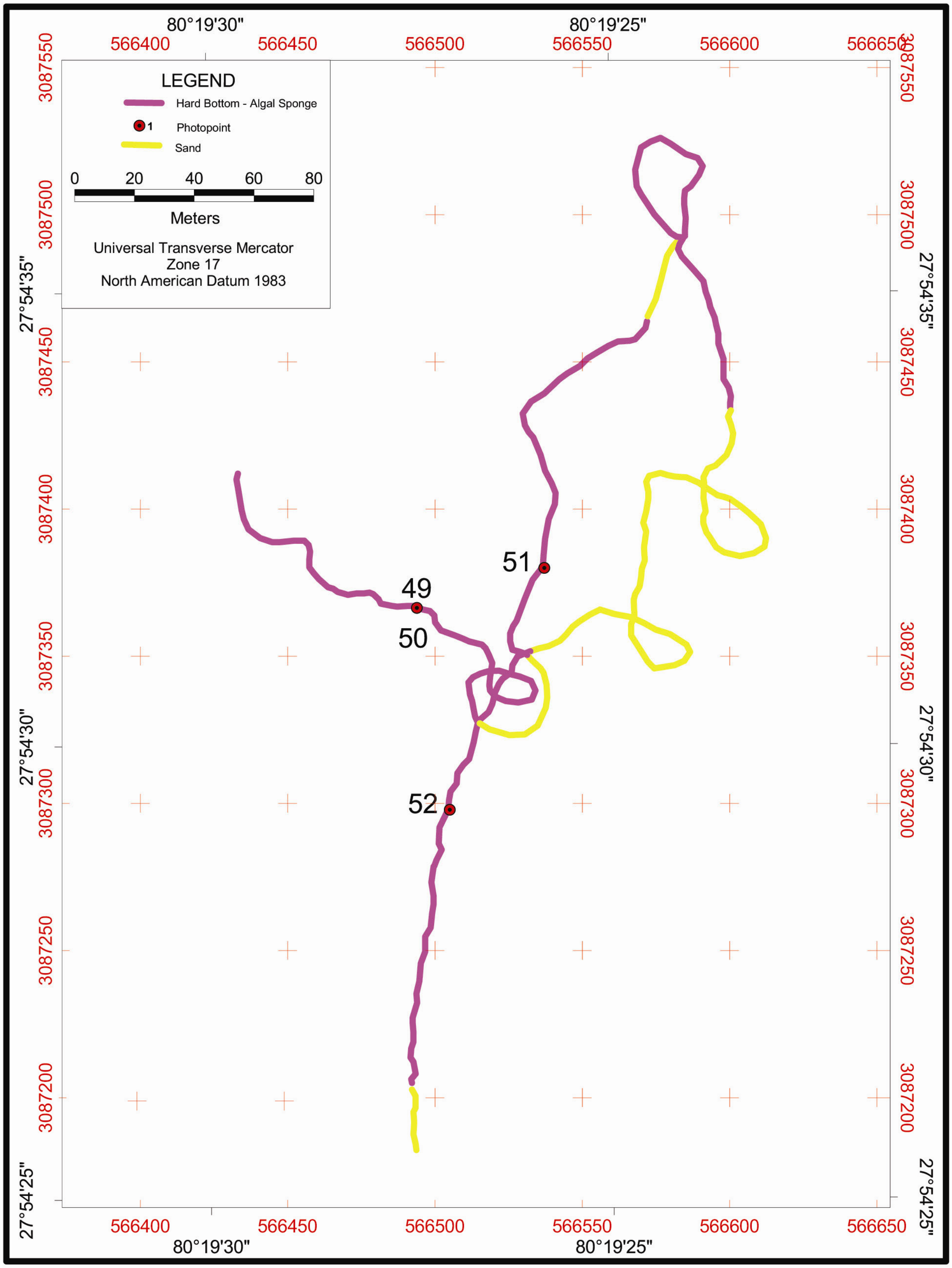

Figure 6-23. Video and still photographic transect surveyed at hard bottom Site 4 during October 2002.

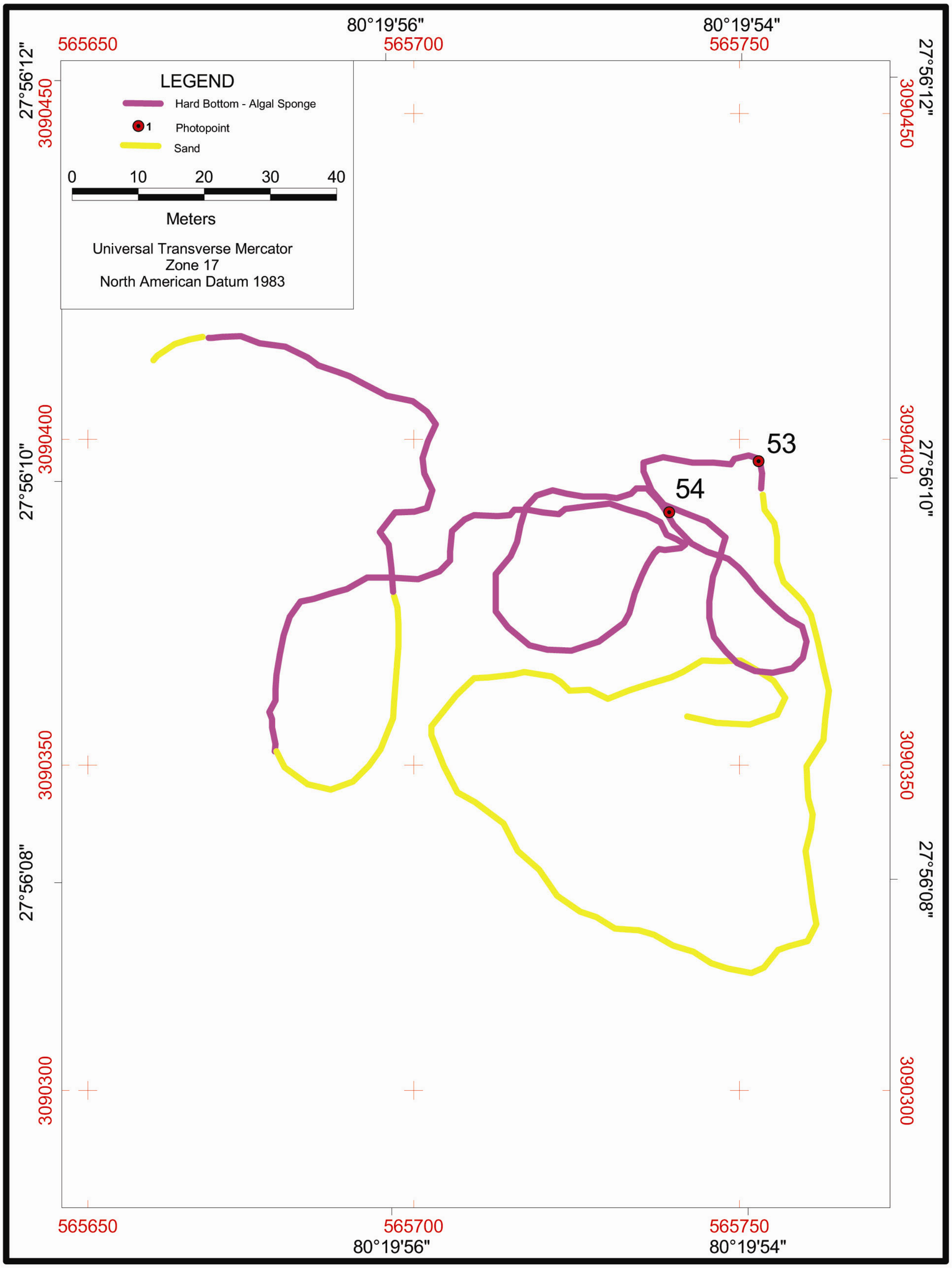

Figure 6-24. Video and still photographic transect surveyed at hard bottom Site 5 during October 2002.

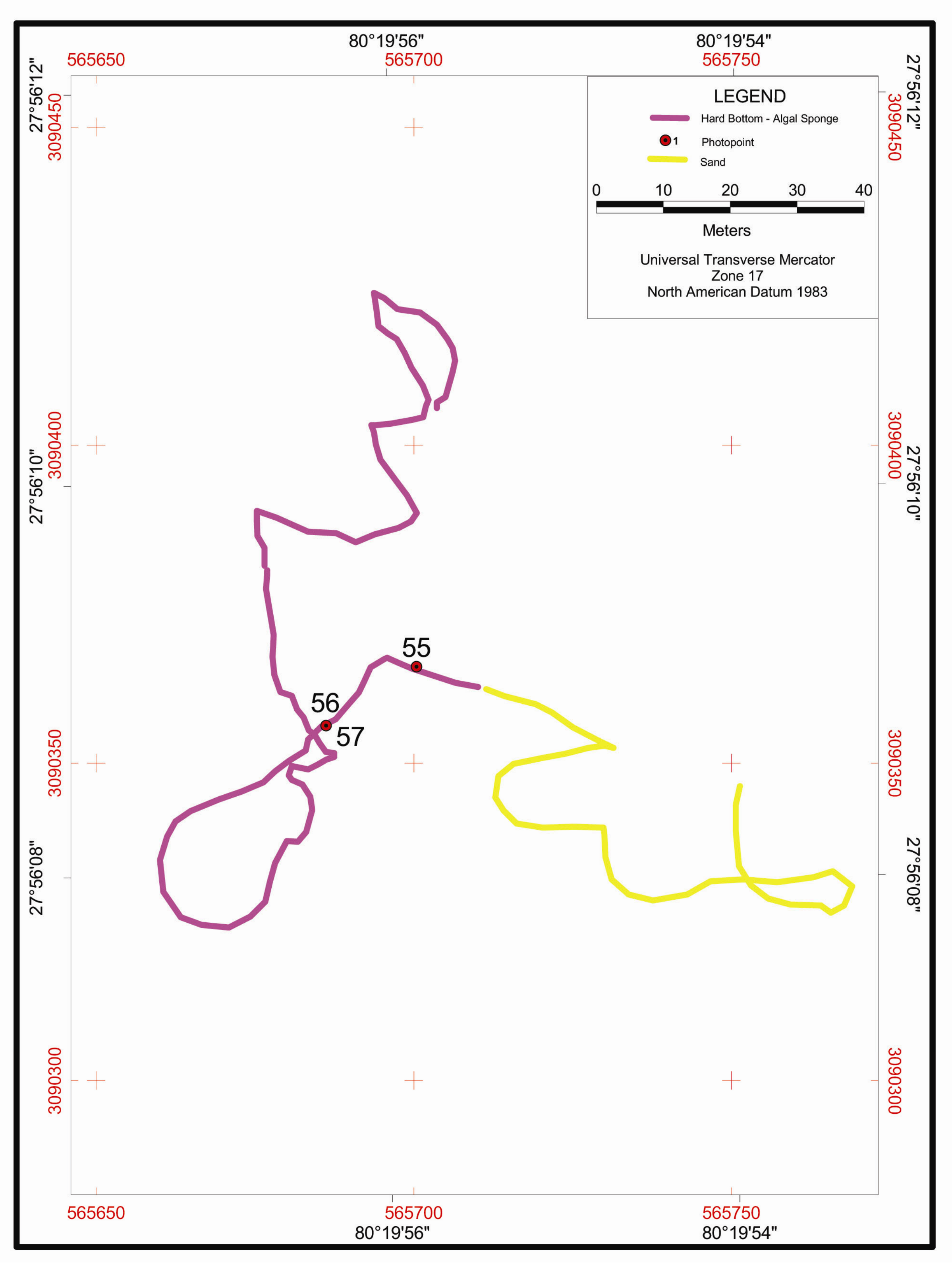

Figure 6-25. Video and still photographic transect surveyed at hard bottom Site 6 during October 2002.

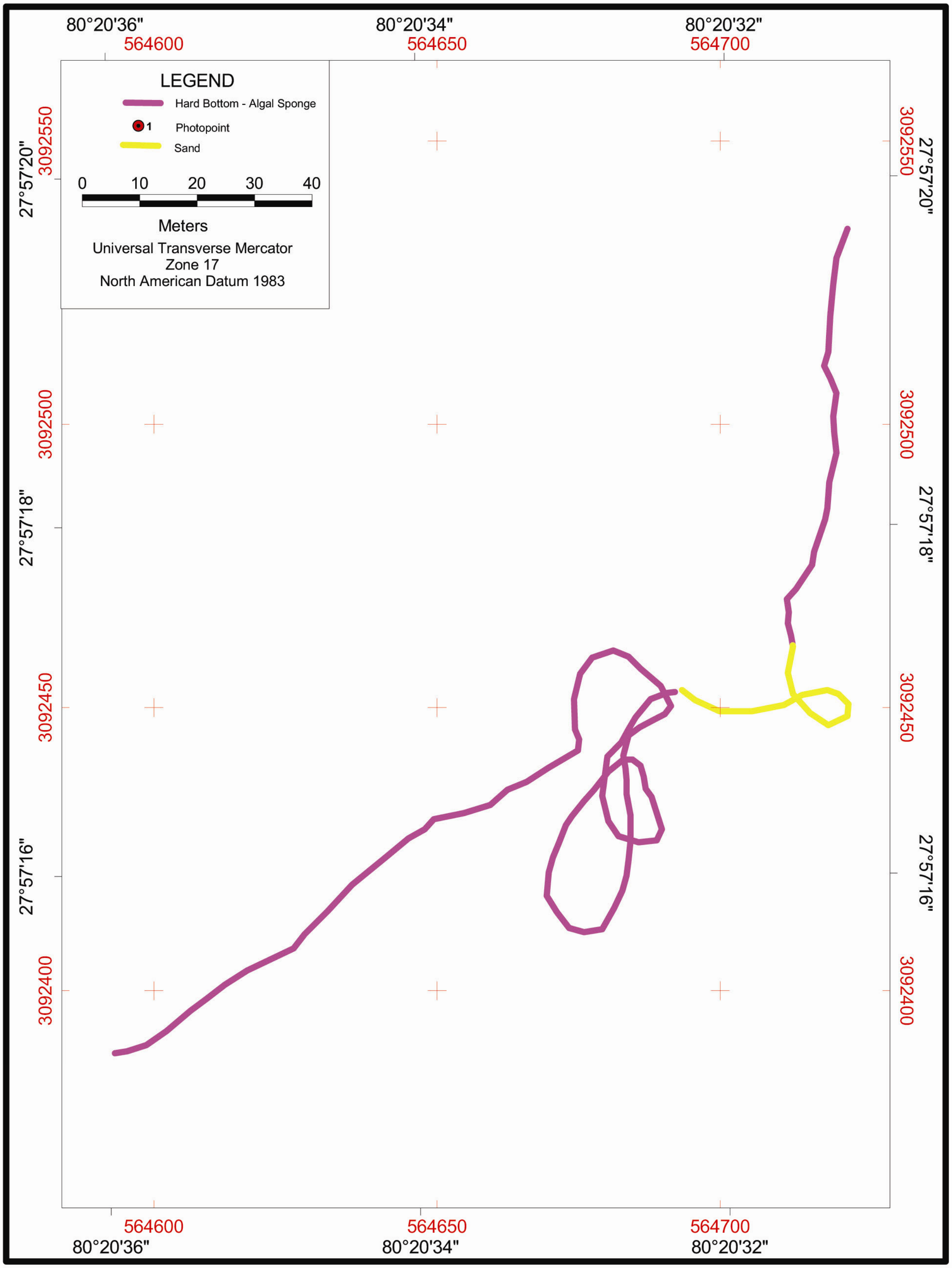

Figure 6-26. Video and still photographic transect surveyed at hard bottom Site 7 during October 2002.

Table 6-11. Fishes observed in video and still images collected during southern (April 2002) and northern (October 2002) hard bottom surveys.

Family	Common Name	Species Name	Southern	Northern
Carcharhinidae	Requeim shark	*Carcharhinus* sp.	x	
Dasyatidae	Southern stingray	*Dasyatis americana*	x	
Serranidae	Black sea bass	*Centropristis striata*	x	x
	Sand perch	*Diplectrum formosum*		x
	Red grouper	*Epinephelus morio*	x	x
	Black grouper	*Mycteroperca bonaci*	x	
	Scamp	*Mycteroperca phenax*	x	
	Whitespotted soapfish	*Rypticus maculatus*	x	
	Belted sandfish	*Serranus subligarius*		x
Priacanthidae	Bigeye	*Priacanthus arenatus*	x	
Apogonidae	Twospot cardinalfish	*Apogon pseudomaculatus*		x
Carangidae	Yellow jack	*Caranx bartholomaei*	x	
	Round scad	*Decapterus punctatus*		x
Lutjanidae	Mutton snapper	*Lutjanus analis*	x	
	Gray snapper	*Lutjanus griseus*	x	x
	Lane snapper	*Lutjanus synagris*	x	
Haemulidae	Black margate	*Anisotremus surinamensis*	x	
	Porkfish	*Anisotremus virginicus*	x	x
	Tomtate	*Haemulon aurolineatum*	x	x
	Cottonwick	*Haemulon melanurum*	x	
	Sailors choice	*Haemulon parra*	x	
	White grunt	*Haemulon plumieri*	x	x
Sparidae	Sheepshead	*Archosargus probatocephalus*	x	x
	Sheepshead porgy	*Calamus penna*	x	
	Porgy	*Calamus* sp.		x
	Silver porgy	*Diplodus argenteus*	x	
Sciaenidae	Cubbyu	*Equetus umbrosus*	x	x
Mullidae	Spotted goatfish	*Pseudupeneus maculatus*	x	x
Chaetodontidae	Spotfin butterflyfish	*Chaetodon ocellatus*	x	x
	Reef butterflyfish	*Chaetodon sedentarius*	x	
Pomacanthidae	Blue angelfish	*Holacanthus bermudensis*	x	x
	Queen angelfish	*Holacanthus ciliaris*	x	
	Gray angelfish	*Pomacanthus arcuatus*	x	x
Pomacentridae	Sunshinefish	*Chromis insolatus*	x	
	Bicolor damselfish	*Stegastes partitus*	x	
	Cocoa damselfish	*Stegastes variabilis*		x
Labridae	Slippery dick	*Halichoeres bivittatus*	x	x
	Yellowhead wrasse	*Halichoeres garnoti*	x	
	Hogfish	*Lachnolaimus maximus*	x	
	Bluehead	*Thalassoma bifasciatum*	x	
Sphyraenidae	Great barracuda	*Sphyraena barracuda*	x	x
Malacanthidae	Sand tilefish	*Malacanthus plumieri*	x	
Gobiidae	Blue goby	*Ptereleotris calliuris*	x	
Acanthuridae	Doctorfish	*Acanthurus chirurgus*	x	x
	Blue tang	*Acanthurus coeruleus*	x	
Scombridae	Mackerels	*Scomberomorus maculatus*		x
Balistidae	Gray triggerfish	*Balistes capriscus*	x	x
Ostraciidae	Scrawled cowfish	*Lactophrys quadricornis*	x	
	Trunkfish	*Lactophrys trigonus*	x	
Diodontidae	Porcupinefish	*Diodon hystrix*	x	
Tetraodontidae	Puffer	*Sphoeroides* sp.		x
Total			43	24

6.4 DISCUSSION

Benthic assemblages surveyed from sand resource areas offshore central east Florida consisted of infauna, soft bottom epifauna and demersal fishes, and hard bottom epibiota and demersal fishes. The assemblages included members of the major invertebrate and vertebrate groups that commonly occur in the study area.

Numerically dominant infauna included numerous polychaetes, mollusks, and crustaceans. Infaunal taxa generally were associated with particular sedimentary habitats. Canonical discriminant analysis of infaunal data indicated that benthic assemblages were affected mostly by the amount of very fine sediments in benthic grabs, primarily silts and to a lesser degree clays. Most animal-sediment associations detected in the data are consistent with observations from other benthic investigations in the western Atlantic (Pearce et al., 1981; Weston, 1988; Barry A. Vittor & Associates, Inc., 1991, 2000; Chang et al., 1992). Infaunal assemblages include 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). Very few infaunal taxa in this study were distributed across a broad sedimentary regime. Most taxa were restricted to stations with varied amounts of measurable fines, measurable gravel, or pure sand. Relatively ubiquitous taxa in the sand resource areas during September and June included the bivalve *Crassinella lunulata* and polychaete *Goniadides carolinae*, and these taxa were among the most abundant collected in grab samples.

Stations with surficial sediments containing measurable gravel yielded taxa that were rare at sand and mud stations. Gravel-inhabiting species included the amphipod *Maera caroliniana*, bivalves *Anomia simplex* and *Pitar fulminatus*, gastropods *Calyptraea centralis* and *Caecum johnsoni*, and polychaetes *Dentatisyllis carolinae*, *Eunice unifrons*, *Exogone lourei*, *Parapionosyllis longicirrata*, and *Sphaerosyllis piriferopsis*. Infaunal taxa that were abundant in sand but not in sediments with measurable gravel included the amphipods *Acanthohaustorius intermedius*, *Bathyporeia parkeri*, *Eudevenopus honduranus*, and *Metharpinia floridana*, and polychaetes *Armandia agilis* and *Goniada littorea*. Certain of these sand taxa also were collected from stations with relatively greater silt and clay fractions; however, a distinct mud assemblage was found as well.

The inverse cluster analysis resolved Species Group 3, which included taxa that were found predominantly at muddy sand stations. This group included the bivalves *Lucina radians* and *Semele proficua*, polychaetes *Magelona* sp. H, *Paraprionospio pinnata*, and *Scoletoma verrilli*, and scaphopod mollusk *Dentalium texasianum*. Fine-textured sedimentary habitats generally provide occluded interstitial space and accumulated organic material that limits inhabiting fauna to surface and subsurface deposit-feeding burrowers. Several benthic investigations have found that the amount of very fine sediments (i.e., clay or silt) is a key determinant of infaunal population distributions in soft bottom environments (Sanders, 1958; Nichols, 1970; Flint and Holland, 1980; Weston, 1988). This type of fine sediment assemblage, including many of the same taxa collected in this study, was collected during a previous investigation offshore Cape Canaveral (Barry A. Vittor & Associates, Inc., 1991).

Within sand resource areas, grain size analyses of samples from sediment-only stations were similar to sediments at stations analyzed for both sediments and infauna. Because of high correlation between sediment type and infaunal assemblage composition, it is likely that assemblages within individual sand resource areas are largely homogeneous, particularly Areas A1, A2, A3, B1, B2, C1, and C2, where sediments varied little between stations.

In addition to effects of sediment type on sample composition, cluster analysis of infaunal data detected between-survey differences. Overall mean species richness and individual abundance values were greater in September than in June. These temporal differences are due primarily to life history characteristics of infaunal populations, in which reproduction peaks during warm months and is diminished during cool months (Sastry, 1978).

Normal cluster analysis resulted in Station Groups B (39 stations) and C (33 stations) that were composed of samples collected at gravelly sand stations during September and June, respectively. Between-survey differences at these stations were due primarily to the September presence of species that were largely or completely absent in June samples, such as the polychaetes *Ceratonereis mirabilis*, *Dentatisyllis carolinae*, and *Nereis riisei* and bivalves *Anadara ovalis*, *Anomia simplex*, *Chione cancellata*, *Crassinella martinicensis*, and *Ervilia concentrica*. Unlike stations with measurable gravel, areas of finer sediments were more similar in infaunal composition across surveys. Station Group A (which mostly included sand stations) and Group E (which included sand stations and all stations with measurable mud) included both September and June samples. Sand stations (Group A) yielded burrowing amphipods during both surveys. There were between-survey differences at mud stations, however, mainly because mud-dwelling infauna (Species Group 3) were more abundant in September samples.

In addition to sedimentary habitat and survey month, discriminant analysis indicated that infaunal assemblage differences between stations were correlated somewhat with water depth. Absolute depth is known to affect the composition of benthic assemblages (Day et al., 1971; Flint and Holland, 1980; Tenore, 1985) and is manifest in different infaunal communities at inner-, mid-, and outer-shelf depths at least partly irrespective of sediment type. It is unclear, however, whether infaunal differences were a reflection of station depth or perhaps were due ultimately to sedimentary or hydrologic variation between stations. Except for the northernmost Area A1 (where the shallowest stations were) and southernmost Areas D1 and D2 (where the deepest stations were), station depths were similar throughout most of the study area. Station Group A, composed of stations with similar assemblages, did include the shallowest stations in the study. Group D stations were confined to deeper stations in Areas D1 and D2. The four stations in Group D differed with respect to sediments, including a muddy sand station and a gravelly sand station, suggesting that effects of water depth on assemblages may have been real, and not related primarily to sedimentary habitat. It is possible also that the narrowness of the shelf and proximity of the Gulf Stream to the southern portion of the study area influenced the infaunal community in this area. Near the southern portion of the study area, the inner edge of the Gulf Stream is usually less than 10 km offshore and can influence faunal composition on the inner shelf (Lyons, 1989).

Common epifaunal taxa in the trawls were various decapods, sand dollars, and squids. Individual abundance was dominated by relatively few species during both surveys. The most abundant species collected during September were the mantis shrimp (*Squilla empusa*), iridescent and blotched swimming crabs (*Portunus gibbesii* and *P. spinimanus*, respectively), unidentified squids, white shrimp (*L. setiferus*), longnose spider crab (*Libinia dubia*), blue crab (*Callinectes sapidus*), and calico box crab (*Hepatus epheliticus*). These eight taxa collectively accounted for 89% of the total epifaunal catch during September. The most abundant species collected during June were the sand dollars *Encope michelini* and *Mellita isometra*, spider crab *Libinia dubia*, and calico scallop (*Argopecten gibbus)*. These four taxa collectively accounted for 86% of the total epifaunal catch during June. Most of the common epifaunal taxa collected are widely ranging species that occur in tropical, subtropical, and temperate environments of the western North Atlantic. Many of these common epifaunal invertebrates have been collected previously in the study area, including the calico scallop, calico box crab, swimming crabs, white shrimp, and sand dollar *E. michelini* (Continental Shelf Associates, Inc., 1987).

During September, 90% of all epifaunal individuals were collected from Areas A1, A2, and A3. Epifaunal taxa were heterogeneously distributed during June, except for *E. michelini* and *L. dubia*, which were collected from multiple stations. These between-survey differences in epifaunal distribution may have been due to seasonal changes in water temperature, which is a primary environmental regulator of the distributions of motile epifaunal populations (Cerame-Vivas and Gray, 1966; Wenner and Read, 1982).

Fishes collected by trawling in the nine sand resource areas reflected the transitional regional species pool of central east Florida that includes a complex of tropical, subtropical, and warm temperate taxa (Gilmore, 1995). The fish assemblage found during September in Area A was similar in terms of species composition to that found previously in the Cape Canaveral area (Anderson and Gehringer, 1965; Wenner and Sedberry, 1989). This shelf assemblage is part of the warm temperate/temperate (Carolinean) fauna that generally ranges from Cape Canaveral north to Cape Fear, NC (Wenner and Sedberry, 1989) and is numerically dominated by sciaenids (croakers and drum) and elasmobranchs (sharks and rays). This assemblage gradually changes in a southerly direction from Area A, with warm temperate species dropping out and more subtropical and tropical species occurring towards southern Areas C and D. Species collected in these southern areas were all members of the regional list for the benthic open shelf habitat compiled by Gilmore et al. (1981). Areas C and D yielded fewer individuals and species than the northern sand resource areas, but occurrence of some species suggested the presence of hard bottom. Reef species of tropical origin such as reef butterflyfish (*Chaetodon sedentarius*), tomatate (*Haemulon aurolineatum*), and parrotfishes *Cryptotomus roseus* and *Sparisoma* spp. were collected in Area D2. This indicates that at least some low relief hard bottom was present in the area traversed by the trawl. Had there been high relief features along the tow path, the trawl would have snagged the bottom, and this was not the case.

There were considerable differences between the September and June surveys in the composition, diversity, and numbers of fishes caught by trawling, particularly in the northern areas (Areas A1, A2, A3, and B1). This finding reflects seasonal trends in the occurrence and abundance of fishes in the South Atlantic Bight reported by Wenner and Sedberry (1989). Unfortunately, there are no data available on assemblage structure of demersal fishes in shelf habitats south of Cape Canaveral to compare with data from Areas C and D.

Fish species collected were typical members of the regional ichthyofauna and were common in previous surveys of the study area (Gilmore et al., 1981; Wenner and Sedberry, 1989). A variety of life stages were collected ranging from early juveniles to adults. Most species collected are benthic feeders, relying on epifaunal and infaunal invertebrates as a food source.

Results of the benthic surveys of the sand resource areas agree well with previous descriptions of benthic assemblages residing in shallow shelf waters offshore east Florida. Overall, canonical discriminant analysis indicated that sedimentary habitat most affected the composition of infaunal assemblages. Overall, trawl contents were consistent with historic regional investigations. The 36 trawl samples collected provide a reasonable snapshot of the demersal fish assemblages in and around the sand resource areas.

Video and still photographs were used to characterize hard bottom habitats occurring in water depths similar to those of the sand resource areas. Hard bottom was found in similar water depths of Areas B1, B2, C1, C2, D1, and D2. Regions around Areas A1 and A2 were not surveyed because of persistently poor water clarity. Relief and physiography of the hard bottom features changed with increasing latitude. Higher relief features were observed in the southern survey area than in the northern survey area. A sediment cover over low relief hard bottom was commonly observed along the northern area transects but only occasionally in the southern area.

There has been little documentation of hard bottom and associated epibiota off central east Florida. Moe (1963) described hard bottom areas along the east coast based on interviews with local fishers. Meisburger and Duane (1971) described geological characteristics of portions of the shelf between Jupiter Inlet and Cape Canaveral. The Southeast Area Monitoring and Assessment Program-South Atlantic (2001) mapped all available hard bottom information for the region (also see Appendix E). None of these three studies reported hard bottom in the areas surveyed during this project. Palm Beach County Department of Environmental Resources Management has contracted a detailed shelf-wide survey using laser assisted depth sounding (LADS) (B. Howard, 2003, pers. comm., Palm Beach County Department of Environmental Resources Management). This technology provides high resolution mapping of hard bottom features over large areas, but success of LADS surveys is dependent on consistent water clarity, therefore it is not likely to be viable north of Martin County. Palm Beach County's final maps should encompass the southern portion of the present study area in the vicinity of Areas D1 and D2.

Hard bottom formations surveyed were ledges or outcrops of Anastasia limestone generally arranged in north-south trending outcrops usually forming ledges facing west. All hard bottom supported epibiotal assemblages of varying taxonomic composition. From the qualitative perspective provided by the present hard bottom surveys, species, composition, richness, and cover varied with latitude over the entire study region. Taxonomic richness of conspicuous taxa such as ocotocorals, sponges, and algae was greater in the southern portions of the southern survey transect. Hard bottom outcrops south of Area D2 supported dense accumulations of soft corals of several taxa. These assemblages were similar to those described by Goldberg (1973) for southern Florida and many taxa occur in the Bahamas and Caribbean Sea. Epibiota observed north of Area D1 consisted of low-lying encrusting forms with very few octocoral taxa or individuals present. An epibiotal assemblage of algae, sponges, and hydrozoans was present from this area northward. Algae, particularly red and brown taxa, were most common and represented most of the cover observed north of Area D2.

These findings support the claim that the Jupiter Inlet area represents a northern boundary for many tropical marine species (Briggs, 1974; Jaap, 1984). Other tropical species extend their ranges as far north as North Carolina (Briggs, 1974), but it appears that factors occurring in this area, probably temperature and water clarity associated with the

Gulf Stream and its behavior, influence the ecology and distribution of tropical forms in species-specific fashion.

Because of species richness and composition of octocorals and other sensitive epibiota, the southernmost outcrops are likely to be more susceptible to turbidity, sedimentation, and mechanical damage due to dredging than the assemblages on the northern area hard bottom. Certainly hard bottom assemblages throughout the region are susceptible to these impacts, but the southern areas support species not likely to be well adapted to sedimentation and turbidity. In the northern areas near Areas B1 and B2, there was evidence of regular natural burial of low relief hard bottom in several areas surveyed. There was frequent evidence of partial burial of low relief hard bottom features in the video and still photographs. Algae were among the most common epibiota found in that area, and members of this group are adapted to the dynamic physical situations (Renaud et al., 1997). Similarly, the soft coral *Lophogorgia* sp. was the only commonly observed octocoral north of Area D1. This taxon has been shown to be tolerant of sedimentation in high-energy environments (Gotelli, 1988).

Although the aim of the hard bottom surveys was not to identify and map areas of hard bottom within sand resource areas, hard bottom was discovered inside the boundaries of Areas B1, D1, and D2. This highlights the importance of having site-specific hard bottom surveys conducted prior to any sand mining.

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 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., 1993a,b). 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 nine sand resource areas offshore central east Florida. 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 (A. Taylor, 1999, pers. comm., Bean Stuyvesant, LLC). 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 (A. Taylor, 1999, pers. comm.). 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 (A. Taylor, 1999, pers. comm.). As such, both technologies will be evaluated for potential biological effects.

7.1 POTENTIAL SAND BORROW SITES

Nine potential sand resource areas were identified offshore central east Florida in Federal waters by the FGS and MMS. Each area has specific geological and geographical characteristics that make it more or less viable as a sand resource for specific segments of coast. Areas A1, B1, B2, C1, and D2 contain borrow sites with the greatest potential for future use.

All sand resource areas are very similar geologically (medium-to-coarse sand size ridge deposits with relief of 2 m or greater and resource volumes of at least 1 mcm). 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. Although six potential sand borrow sites were designated as ones with greatest potential, it is possible that sand could be dredged from intervening offshore areas and on other offshore shoals.

The amount of dredging that occurs at any site is a function of Federal, State, and local requirements 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 MMS and State personnel. 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 10 to 20 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 without 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 good sand resource management practice to dredge the leading edge of a migrating shoal because 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 threshold for maintaining environmentally-sound 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 areas. 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 central east Florida, 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).

7.2.1 Offshore Cape Canaveral

Canaveral Shoals, the complex of ridges and troughs that extend southeast from Cape Canaveral, caused significant increases in wave height as waves propagated over this area. As 1.0 m, 7.7 sec waves from the east-southeast (Case 3A) refracted around the shoals, wave heights increased by 0.5 m over offshore wave conditions. In the shoal field northeast of the Cape, wave heights increased by about 0.3 m above offshore wave heights. Wave direction changes also were observed in these areas. A greater degree of wave refraction was illustrated for longer period waves. For a 1.6 m, 14.3 sec wave propagating from the east-northeast (Case 6A), wave direction for some nearshore regions adjacent to the Cape changed more than 45 degrees, following the gradient in bathymetric contours (see Figure 4-17). Largest waves in the model domain occurred at shoals northeast of Port Canaveral (1.3 m higher than offshore waves). At shoals in the vicinity of the borrow site in Area A1, wave heights increased to a maximum of 2.8 m, 1.2 m above offshore conditions. Shoals tended to refract wave energy and caused focusing (wave convergence) near the Cape. However, the coast south of the Cape illustrated reduced wave heights (wave divergence).

Post-dredging wave height changes for Case 3A illustrated a maximum wave height increase of 0.2 m and maximum wave height decrease in the shadow zone of the site of 0.3 m. The overall area of influence for the borrow site in Area A1 extended approximately 14 km north of the Cape to about 4 km south of Port Canaveral. Similar wave height differences were illustrated for Case 6A. Maximum change in post-dredging wave heights was 0.7 m, substantially greater than change observed at other sites. The area of greatest wave height increase occurred at the northwest corner of the site. Wave heights did not increase by the same amount at the southwest corner, likely due to local bathymetry and geometry of the site. Deeper excavation depths at the northwest corner cause a greater degree of wave refraction. The longshore extent of influence was similar to that of Case 3A, but its location shifted slightly southward due to the direction of wave propagation. However, for all wave simulation cases, the impact of borrow site excavation on wave height and direction changes was minor relative to natural variability of the local wave climate and transport regime.

7.2.2 Offshore Sebastian Inlet

Wave model output for 1.9 m, 6.9 sec waves propagating from the north-northeast (Case 1B), offshore Sebastian Inlet at borrow sites in Areas B1 and B2, illustrated minor changes throughout the model domain. The shoal encompassing the borrow site in Area B1 had the greatest influence on wave propagation in the region, although effects were small because the shoal had a minimum depth of approximately 12 m NGVD. For wave Case 10B (H_s = 1.7 m, T_{peak} = 10.8 sec), wave height was similar but peak wave period was longer, resulting in greater wave refraction. Wave heights shoreward of the shoal were approximately 0.2 m greater than wave heights on the seaward side of the feature.

Changes in the wave field caused by dredging at borrow sites in Areas B1 and B2 illustrated minor impacts for the Area B model domain. For wave Case 1B, borrow sites had a limited influence on waves over a long section of coast (>30 km), but changes on the order of 0.01 m occurred along 2.5 km of coast landward of the borrow site in Area B1 (see Figure 4-22). Maximum change in wave height was approximately 0.10 m at Area B1 and 0.12 m at the borrow site in Area B2. Even though the borrow site in Area B2 was smaller than that in Area B1 (i.e., less sediment dredged), B2 had a slightly greater impact on local wave heights. This apparent paradox was due to subtle changes in bathymetry relative to borrow site geometry.

Wave differences computed for Case 10B indicated that changes to the wave field resulting from dredging at sand borrow sites in Areas B1 and B2 were more pronounced than for wave Case 1B. The length of shoreline influenced by changes in wave propagation from the two borrow sites was approximately 20 km; however, greatest changes occurred within a 12 km stretch of coast. At Area B1, maximum changes in wave height were 0.13 m, very similar to those computed for the borrow site in Area B2. Although the magnitude of maximum wave height change for wave Case 10B was only slightly larger than 1B, shoreline impacts associated with 10B were quite a bit greater. Long period waves of Case 10B were affected more by bathymetry in deeper water, causing larger areas of waves on the shoals to be impacted by dredging at borrow sites. This process resulted in a broader area of impacted shoreline. However, for all wave simulation cases offshore Sebastian Inlet, the impact of borrow site excavation on wave height and direction changes was minor relative to natural variability of the local wave climate and transport regime.

7.2.3 Offshore St. Lucie Inlet

For the wave model domain offshore St. Lucie Inlet, 1.5 m, 7.5 sec waves propagating from the northeast (Case 2C) illustrated slight wave focusing at shoals within the designated borrow site boundaries. The minimum depth at Site C1 north was 7.6 m NGVD, and 5.4 m NGVD was the minimum depth at Site C1 south. Because shallower depths exist in these areas, waves passing over the shoals refracted toward the shoreline sooner than in other areas the same distance offshore. Waves refracting over the shoals produced an area of increased wave heights landward of each shoal and a corresponding area of decreased wave heights immediately south of both sites. For C1 north, maximum wave height increase was 0.18 m, and the maximum decrease was 0.39 m. Similar changes were observed at C1 south, where the maximum increase in wave height was 0.13 m and the maximum decrease was 0.33 m. For wave Case 10C, a 1.1 m, 11.1 sec wave from the east, wave height changes at C1 north and C1 south were not as large as those for Case 2C, but wave energy was still focused behind the shoals. This focusing caused a zone of increased wave heights that extended to the shoreline. Unlike the results of Case 2C, where wave height changes at the borrow sites were more pronounced, the resulting wave shadow zone diffused more as it approached the shoreline (due to the shorter peak wavelength of Case 2C).

For wave Case 2C, wave height differences resulting from dredging Sites C1 north and C1 south indicated a strong interaction between the two sites because C1 south was partially within the shadow zone of C1 north. The alignment of borrow sites caused a single area of increased wave heights at the shoreline (approximately 4 km long) and a more diffuse zone of reduced wave heights (extending 12 km south toward St. Lucie Inlet). At the borrow sites, maximum wave height increase was 0.09 m, and the maximum wave height decrease was 0.15 m. Wave height differences for wave Case 10C illustrated that the borrow sites have an overlapping influence at the shoreline for waves propagating from the east, even though one site was not directly in the shadow of the other. The total length of affected shoreline was approximately 16 km, and changes at the borrow sites were similar in magnitude to those for Case 2C. The resulting wave shadow zone for the two borrow sites was less diffuse due to a longer peak wavelength for this model case.

7.2.4 Offshore Jupiter Inlet

The primary bathymetric feature impacting wave propagation in modeled Area D is located approximately 5.6 km offshore Jupiter Inlet. The shoal has a minimum water depth of 11.7 m NGVD, and the borrow site in and adjacent to Area D2 lies along the seaward margin of the shoal at the Federal-State boundary. For wave Case 1D (1.4 m, 6.9 sec wave from the NNE), the shoal produced a slight focusing of waves seaward of the shoal and an area of reduced wave heights 2.6 km along the shoreline north of Jupiter Inlet. Similar results were documented for wave Case 9D, a 1.3 m, 13.0 sec wave from the ENE. Wave heights increased behind the shoal, and a 4.9 km stretch of coastline north of Jupiter Inlet experienced increased wave heights. Maximum wave height increase caused by the shoal for Case 9D was 0.4 m, whereas Case 1D produced a 0.1 m change in wave height.

Wave height changes resulting from dredging Borrow Site D2 showed greatest change at the north end of the site where the deepest excavation occurred. The maximum increase and decrease in wave height that resulted for wave Case 1D was 0.04 and 0.05 m, respectively. This small change relative to changes at borrow sites to the north was due to greater water depths at and seaward of the borrow site. For wave Case 9D, two shadow areas of reduced wave heights propagated from two separate areas within the borrow site, but join to form one shadow on the shoreward side of the shoal. This change pattern occurred because the original bathymetry within Site D2 contained two elevation peaks approximately 1.5 m higher than the surrounding shoal surface. Overall, wave simulation cases offshore Jupiter Inlet illustrated minor wave height and direction changes in response to borrow site excavation relative to natural variability of the local wave climate and transport regime.

7.3 CURRENTS AND CIRCULATION

Circulation patterns along the central east Florida coast near potential offshore borrow sites were investigated using current meter observations obtained offshore St. Lucie Inlet and over Thomas Shoal, seaward of Sebastian Inlet. Analysis of historical data indicated that circulation patterns consisted predominantly of along-shelf currents that reversed direction approximately every 2 to 10 days. Current reversals were found weakly correlated with local wind stress; literature suggested that subtidal variability was due to meanders or spin-off eddies of the Florida Current. Peak speeds were on the order of 40 to 50 cm/sec at mid-shelf and inner-shelf locations and were directed either upshelf (to the north-northwest) or downshelf (to the south-southeast). Strongest currents were most commonly directed to the north. Tidal currents contributed significantly to inner-shelf current observations;

however, these observations were obtained near the tidally-dominated St. Lucie Inlet and may not be reflective of inner shelf regions removed from major coastal inlets.

ADCP measurements in the vicinity of Thomas Shoal offshore Sebastian Inlet also were dominated by along-shelf flows that correlated with seasonal changes in wind. May survey conditions were dominated by winds from the south, while September survey conditions were characterized by short wind events from the north. Current measurements illustrated a mean flow directed to the north during spring and to the south in fall. This seasonal directionality of flow was supported by historical data and literature regarding observations on the mid-shelf and inner-shelf where sand resource areas have been identified. Strongest currents flowed to the south at 30 cm/sec during the September survey in response to northerly winds.

Seasonal wind variations have been shown to induce downwelling in winter and upwelling in summer for central east Florida. Current variability not well explained by wind stress may be an indirect response to the Florida Current. The Florida Current flows northward past the study area on the outer shelf (Lee et al., 1985). Instabilities in the Florida Current create spin-off eddies that have been documented on the inner shelf (Smith, 1981). Potential influences of the Florida Current were observed in spring survey results, illustrated by the presence of a strong northward flowing bottom current in the presence of weak winds and surface currents. Florida Current effects may enhance northerly flows during winter and spring months in the study area.

In shallow waters, over shoals and adjacent to tide-dominated inlets such as St. Lucie, cross-shelf tides may influence current velocities. May and September field data showed onshore currents dominated across the shoal. During the May survey, onshore currents were enhanced by flood tide. Tidal dependence was not observed during the September survey. On the inner- to mid-shelf, in the vicinity of the sand resource areas, tidal effects are secondary to wind effects. In the presence of local bathymetric features, such as Thomas Shoal, steering and sheltering of flow across the shoal were observed. Under average conditions, currents were steered onshore across the shoal. In the presence of dominant winds, near-bottom currents flowed parallel to bathymetric contours.

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 resulting dredging will not remove enough material to significantly alter major bathymetric features in the region. Therefore, the forces and/or geometric features that principally affect circulation patterns will remain relatively unchanged.

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, potential longshore sediment transport was computed using wave modeling output to estimate potential impacts along the coast (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 1877/83 to 2002 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 bathymetric change documented four important trends relative to study objectives. First, the predominant direction of sediment transport on the continental shelf and along the outer coast between Cape Canaveral and Jupiter Inlet was north to south. The greatest amount of shoreline change in this study was associated with beaches adjacent to Cape Canaveral, Port Canaveral Entrance, and beaches south of St. Lucie Inlet.

Second, the most dynamic features within the study area, in terms of nearshore sediment transport are the beaches and shoals associated with Cape Canaveral. Areas of significant erosion and accretion are documented between 1956 and 1996 at Cape Canaveral, reflecting wave and current dynamics and the contribution of littoral sand transport from the north to shoal and spit migration. Depositional zones also were prominent in the shoal regions along the inner shelf from Fort Pierce south to Jupiter Inlet. Large quantities of carbonate and shell fragments observed in sediment samples collected from shoals in this region indicated that much of the deposition in this portion of the study area may have been locally produced.

Third, alternating bands of erosion and accretion documented between 1956 and 1996 at Cape Canaveral illustrated steady reworking of the upper shelf surface as sand ridges migrated from north to south. The process by which this was occurring at Sand Resource Area A1 suggested that the borrow site in this region would fill with sand transported from the adjacent seafloor at rates ranging from 88,000 to 119,000 m^3/yr. Areas of erosion and accretion documented between 1929/31 and 1929/73 between Port Canaveral Entrance and Jupiter Inlet indicated the amount of sediment available for infilling sites south of Port Canaveral Entrance was between 38,000 and 113,000 m^3/yr.

Finally, net longshore transport rates determined from seafloor changes in the littoral zone between Cape Canaveral and Port Canaveral Entrance, in conjunction with dredging records for Port Canaveral entrance, indicated maximum transport rates near Cape Canaveral, with lower rates south of the entrance. Net longshore transport north of Port

Canaveral entrance was estimated at about 236,000 m^3/yr (308,000 cy/yr). South of the Port, rates have been estimated to range from 119,000 m^3/yr (155,000 cy/yr) immediately south of the entrance to 140,000 to 184,000 m^3/yr (183,000 to 240,000 cy/yr) between Fort Pierce and Jupiter Inlet.

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 borrow 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 5,000 m^3/yr (Site D2) to a high of about 538,000 m^3/yr (Site A1), while the infilling time varied from 25 to >500 years. Site A1 had the greatest infilling rate due to its shallow water depth relative to the other sites and its large perimeter. Because Site A1 is in shallow water, wave-induced and wind-driven currents were larger than at deeper sites, and more sediment was mobile in the proximity of the borrow site. Furthermore, sites that have a larger surface area generally trap more sediment in a given time period.

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 D2 has the longest total infilling time, resulting from relatively deep water depths and the low infilling volume rate computed for the area. Even though Site A1 had the largest sand extraction volume, the infilling time was shortest due to its large sediment 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 may change. As such, sediment transport rates will fluctuate as a borrow site evolves during infilling. These estimated infilling times are most useful as a relative guide for borrow site infilling rather than an absolute indicator of exactly how long it takes for the borrow site to fill. The analysis performed provided 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. Mean sediment transport potential calculated for the shoreline south of Port Canaveral indicated strong net southerly transport of approximately 500,000 m^3/yr, which gradually reduced to approximately 300,000 m^3/yr at the southern limit of the model grid. The transport significance envelope was largest (approximately ±300,000 m^3/yr) north of Cape Canaveral and in the southern half of the modeled area (see Figure 4-32).

Mean transport potential computed for Area B (offshore Sebastian Inlet) indicated that net transport potential was generally less than 100,000 m^3/yr to the south. There is an approximate ±500,000 m^3/yr range in net transport rates. Computations indicated that it was possible in some years for net transport potential to be northward directed. Near Vero Beach, net transport potential was to the south at around 500,000 m^3/yr and annual variation in net transport potential was similar (approximately ±500,000 m^3/yr). This may be due to a change in shoreline orientation that occurred at this point.

Computed mean annual transport potential for modeled Area C (just north of St. Lucie Inlet) was to the south, ranging from approximately 400,000 m^3/yr at the northern boundary of the grid to approximately 100,000 m^3/yr at the southern limit near St. Lucie Inlet (see Figure 4-36). Sand transport potential calculations for 20 individual years indicated that the annual variability in transport potential had a range of approximately ±400,000 m^3/yr to the north that gradually decreases to approximately ±200,000 m^3/yr at the southern limit of the modeled area. Along some sections of the modeled shoreline, it was possible to have net northerly-directed transport during some years.

Net transport along the coastline adjacent to Jupiter Inlet varied from about 200,000 m^3/yr to the south near the northern limit of the area to about 500,000 m^3/yr to the south near Jupiter Inlet (see Figure 4-38). Results from the 20 individual modeled years showed that the annual variability ranged from approximately ±150,000 m^3/yr in the northern part of the area to approximately ±300,000 m^3/yr at the southern extent of the model grid. Similar to modeled areas to the north, the year with greatest modeled southerly transport was 1980, and the year with greatest northerly transport was 1990. As with the entire study area south of Cape Canaveral, net transport potential was always to the south and transport variability was large.

The significance of changes to longshore transport along the modeled shoreline resulting from dredging proposed borrow sites to their maximum design depths was determined using the method described in Kelley et al. (2004). Model output for the region south of Cape Canaveral (Area A) indicated that the significance envelope was approximately 20% of the mean computed net transport potential in the area of greatest impact from the borrow site in Area A1. The maximum modeled decrease in south-directed transport for post-dredging conditions was about a 40,000 m^3/yr (within the transport significance range), just south of Port Canaveral. For the Area B borrow sites (adjacent to Sebastian Inlet), the transport significance range was nearly consistent at about ±100,000 m^3/yr. The impacts that resulted from numerically dredging Borrow Sites B1 and B2 are within this transport range, indicating that these sites would not produce significant modifications to coastal processes along the shoreline. The largest calculated differences between existing and post-dredging transport potential occurred north of Sebastian Inlet (where the transport rate becomes more southerly by 30,000 m^3/yr) and just south of the inlet (where transport rates become less southerly by 30,000 m^3/yr).

For Borrow Sites C1 north and C1 south (north of St. Lucie Inlet), the computed longshore transport significance range was approximately ±100,000 m^3/yr at the northern limit of the area and ±50,000 m^3/yr at the southern limit. Potential impacts from dredging Sites C1 north and C1 south to a maximum excavation depth of -12 m indicated that the significance envelope was exceeded along a 2-km length of shoreline approximately 18 km north of St. Lucie Inlet. At the point of maximum dredging-induced change along the shoreline, the significance level was ±60,000 m^3/yr, and the computed change in transport potential was 85,000 m^3/yr. As designed, borrow site configuration may not be acceptable. If a borrow site redesign were required, the most likely change would be a reduction in maximum dredging depth to reduce site impacts.

The envelope of significant change in potential longshore transport rates under natural wave propagation conditions for Borrow Site D2 ranged from approximately ±50,000 m^3/yr in the north to ±100,000 m^3/yr in the south, with a maximum of approximately ±150,000 m^3/yr occurring just north of Jupiter Inlet. Modeled dredging impacts to transport potential for Site D2 were minimal; predicted changes were well within the transport variability significance range. Maximum dredging impacts to transport potential were approximately ±10,000 m^3/yr. Small impacts for this area (compared with previous modeled areas) resulted from larger borrow site depths, smaller excavation volume, and the sheltering effect of the shoal landward of D2.

Overall, it was determined that no significant changes in longshore sediment transport potential would result from modeled borrow site configurations for Areas A, B, and D. However, the proposed sites in Area C do have significant impacts to transport potential along the shoreline. Therefore, Area C sites should be redesigned so impacts are within acceptable limits, most likely by reducing the maximum depth of excavation at the sites.

7.5 BENTHIC ENVIRONMENT

The purpose of this section is to address potential effects of offshore sand dredging on benthic organisms, including analyses of recolonization periods and success following cessation of dredging. This section is divided into three parts. The first two parts provide reviews of information from existing literature on effects and recolonization. The first part (Section 7.5.1) summarizes potential impacts to benthic organisms from physical disturbance of dredging, which causes removal, suspension/dispersion, and deposition of sediments. The second part (Section 7.5.2) is a synthesis of information concerning recolonization periods and success. Finally, the third part (Section 7.5.3) provides predictions of impacts and recolonization relative to the central east Florida sand resource areas.

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., 1993a,b; 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 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 resource areas.

7.5.1 Effects of Offshore Dredging on Benthic Biota

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, which may make the benthic environment less suitable for some species and better for other biota. The following subsections focus on potential effects of these physical processes on benthic biota.

7.5.1.1 Sediment Removal

Physical removal of sediments from a borrow site removes benthic habitat along with infauna and epibiota that are incapable of avoiding the dredge, resulting in drastic reductions in 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 the resources 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). In some cases, dredging borrow sites may create new and different habitats from surrounding substrates, which could result in beneficial impacts in terms of 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), Jones (1950), 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 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). Selective bottom feeders could be affected due to removal of specific prey species from borrow sites. The State of Florida and Florida Keys National Marine Sanctuary (FKNMS) prohibited collection of “live sand” (i.e., sand material, typically containing a high diversity of algal, bacterial, and macroinvertebrate species, used in the aquarium trade industry) within the FKNMS because the sand substrate is an important habitat for grazers and detritovores and removal of this habitat was determined to adversely impact marine productivity, fisheries, wildlife habitat, and water quality (Ruebsamen, 2003).

Removal of sediments from borrow sites can alter seabed topography, creating pits that may refill rapidly or cause detrimental impacts for extended periods of time. The term "borrow site" can be misleading because often material is returned only by natural sediment transport processes. Nearly 12 years may be required for some offshore borrow sites to refill to pre-dredge profiles (Wright, 1977), and other borrow sites have been known to remain well-defined 8 years after dredging (Marsh and Turbeville, 1981; Turbeville and Marsh, 1982). Intentionally locating borrow sites in highly depositional areas may dramatically reduce the time for refilling (Van Dolah et al., 1998). In general, shallow dredging 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. Increasing water depths and turbidity from dredging may reduce the photic zone for benthic primary producers. 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). Not all impacts from dredge pits are detrimental. Borrow pits are known to attract numerous fishes (Gustafson, 1972; Michals, 1997; Weakley, 2001), even to the extent that some dredge holes offshore east Florida have been referred to as "reefs in reverse" (Weakley, 2001). Borrow pits also provide resting places for loggerhead sea turtles (Michals, 1997).

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 several studies to address environmental questions concerning use of shoals by fishes and mobile invertebrates, 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 1 year after dredging disturbance except recovery of average sand dollar weight and biomass composition, which required 2.5 years.

Mechanical damages to hard bottom habitats and biota have occurred in the past from dredges digging into and equipment (e.g., anchors, cables, pipelines, etc.) being dragged across reefs (Courtenay et al., 1972, 1974; Britt & Associates, Inc., 1979; Marszalek, 1981; Blair and Flynn, 1988; Goldberg, 1989; Blair et al., 1990). These occurrences often are unnecessary and avoidable if borrow sites and adjacent areas are adequately surveyed for hard bottom prior to dredging, then mitigation and monitoring are implemented. Reef destruction can lead to shifts from coral to algal dominance (de Sylva, 1994; Umar et al., 1998; McCook et al., 2001). Randall (1958) pointed to the correlation between availability of new surfaces in the reef environment, rapid growth of algae, and development of ciguatera (toxicity in normally edible reef fishes causing human health problems). Dredging, filling, anchoring, and other anthropogenic activities leading to changes in a reef environment or coral reef destruction may increase the incidence of ciguatera, known to occur irrespective of season along the Florida east coast, including locations near the study area (de Sylva, 1994).

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 water currents, then suspended sediments from dredging settle. The extent of suspension/dispersion depends on a multitude of factors, incluing the type of dredging equipment, techniques for operating the equipment, amount of dredging, thickness of the dredged layer, sediment composition, and sediment transport processes. Although turbidity plumes associated with dredging often are short lived and affect relatively small areas (Cronin et al., 1970; Nichols et al., 1990), resuspension and redispersion of dredged sediments by subsequent currents and waves can propagate dredge-related turbidity for extended periods after dredging ends (Onuf, 1994). Biological responses to turbidity depend on all of these physical factors coupled with the type of organism, geographic locations, and the time of year.

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

A hopper dredge consists of one, two, or more dragarms and attached dragheads mounted on a ship-type hull or barge with hoppers to hold material dredged from the bottom (Herbich and Brahme, 1991). As the hopper dredge moves forward, 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; Newcombe and Jensen, 1996; Wilber and Clarke, 2001). Turbidity effects may be less important in unprotected offshore areas for several reasons. Offshore sands tend to be coarser with less clay and silt than inshore areas. The open ocean environment also provides more dynamic physical oceanographic conditions, which minimize settling effects. In addition, offshore organisms are adapted to sediment transport processes, which create scouring, natural turbidity, and sedimentation 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. (Sosnowski, 1984; Herbich, 1992). Physical disturbance of the bottom and resulting biological impacts from dredging are similar to those of storms and trawling but at a much smaller spatial scale. The following suggestions from Hughes and Connell (1999) also are instructive regarding the complexities of analyzing effects of multiple stressors (broadly defined as natural or man-made disturbances). Long-term approaches are necessary to understand biological responses to multiple stressors because studying single events in isolation can be misleading. The effects of a particular disturbance often depend critically on impacts from previous perturbations. Consequently, even the same type of recurrent stressor can have different effects at different times, depending on history. Accordingly, when the added dimension of time is considered, the distinction between single and multiple stressors becomes blurred (Hughes and Connell, 1999).

Turbidity from dredging can elicit a variety of benthic responses primarily because attributes of the physical environment are affected (Wilber and Clarke, 2001). 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 photosynthesis and primary productivity of benthic organisms such as algae, seagrasses, and zooxanthellae (symbiotic algae) associated with corals (Phinney, 1959; Courtenay et al., 1972; Owen, 1977; Onuf, 1994). Light has long been known as an ecological factor affecting dispersal and settlement of marine invertebrate larvae (Thorson, 1964). Suspended materials can prevent growth of benthic organisms such as corals and plants that provide habitat complexity and biological structures used by many other species for shelter and egg attachment (Phinney, 1959; Cronin et al., 1969; Owen, 1977; Nelson, 1989; Connell, 1997). Although coral reefs are adapted to transient increases in turbidity, a continuous reduction in light penetration from dredging may drastically reduce respiration and productivity, cause bleaching and death, and lead to severe alterations of community structure and function, particularly in deep reef zones where light is already limiting (Rogers, 1979). From laboratory experiments that did not reduce light intensity or significantly alter spectral quality, Telesnicki and Goldberg (1995) concluded that turbidity induces increases in respiration rather than decreases in photosynthesis of two common scleractinian coral species from Florida, and suggested that adherence to turbidity-related water quality standards in Florida may result in short-term stress and long-term decline in at least some coral species.

Turbidity can affect food availability for benthic organisms. Changes in light penetration and wavelengths due to turbidity can affect visibility and may be detrimental or beneficial, depending on whether an organism is predator or prey. Suspension and dispersion processes uncover and displace benthic organisms, temporarily providing extra food for bottom feeding species (Centre for Cold Ocean Resources Engineering, 1995).

Turbidity can interfere with food gathering processes of filter feeders and organisms that feed by sight by inundation with nonnutritive particles. In addition to altered feeding rates, other biological responses to turbidity include reduced hatching success, slowed growth, abnormal development, tissue abrasion, and increased mortality (Wilber and Clarke, 2001). In general, egg and larval stages are more sensitive to turbidity effects than older life history stages. Although a considerable amount of information is available on the effects of sediment suspension and dispersion to some benthic organisms, little or no information exists for many other species, particularly those associated with hard bottom (Dodge and Vaisnys, 1977; Bak, 1978; Nelson, 1989; Rogers, 1990; Kerr, 1995; Renaud et al., 1996, 1997).

Suspension and dispersion of sediments may cause changes in sediment and water chemistry as nutrients and other substances are released from the substratum and dissolved during dredging. For aggregate mining operations using hopper dredges, the far-field visible plume contains an organic mixture of fats, lipids, and carbohydrates from organisms entrained and fragmented during the dredging process and discharged with the overflow (Coastline Surveys Limited, 1998; Newell et al., 1999). Dredging may produce localized hypoxia or anoxia in the water column due to oxygen consumption of suspended sediments (LaSalle et al., 1991). Flocculation of suspended sediments can mechanically trap inorganic and organic particles and plankton and carry them to the bottom (Bartsch, 1960 as cited in Levin, 1970).

7.5.1.3 Sediment Deposition

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

Deposition of sediments can suffocate and bury hard bottom and soft bottom benthic biota, although some mobile soft bottom organisms are able to migrate vertically to the new surface (Maurer et al., 1986; Nelson, 1988). Unlike most soft bottom biota, many hard bottom organisms are sessile and unable to burrow up through sediment overburden (Nelson, 1989; Wesseling et al., 1999). Heavy sedimentation can result in acute stress and death, and chronic high turbidity can cause stress responses and reductions in health and growth of algae, corals, and other filter feeding organisms (Dodge et al., 1974; Dodge and Vaisnys, 1977; Bak, 1978). Corals and algae with shapes that enable accumulation of sediments are particularly sensitive to depositional effects from mining (Courtenay et al., 1972; Owen, 1977; Bak, 1978; Goldberg, 1985, 1989; Hubbard, 1986; Chansang, 1988; Rogers, 1990; Riegl, 1995). Sediment deposition can negatively affect photosynthetic activity of zooxanthellae and thus the viability of corals (Yentsch et al., 2002; Philipp and Fabricius, 2003). Substantial deposition of sediments in areas of coral growth is of concern, even though many corals can withstand some sedimentation through active removal (Levin, 1970; Courtenay et al., 1972; Rice and Hunter, 1992; Stafford-Smith and Ormond, 1992; Stafford-Smith, 1993; Torres and Morelock, 2002). Corals lose the ability to clean sediments when exposed to extended periods of high turbidity (Clarke et al., 1993). Sediment removal by organisms requires time and energy that otherwise could be used for growth, food capture, reproduction, etc. (Dodge and Vaisnys, 1977; Riegl and Branch, 1995; Dustan, 1999). Growth rates were reduced for some coral species that are efficient sediment rejectors, and colonies of another species lost their symbiotic zooxanthellae and died as a result of sediment cover that they were unable to remove (Bak, 1978). Heavy sedimentation can result in decreased calcification and net productivity of corals, fewer coral species, greater abundance of branching forms, less live coral, lower coral growth rates, reduced coral recruitment, and slower rates of reef accretion (Rogers, 1990). Increased sediment loads can contribute to coral reef degradation and shifts from coral to algal dominance (de Sylva, 1994; Umar et al., 1998; McCook et al., 2001).

Sediment deposition can inhibit larvae of numerous invertebrate species that need hard surfaces to settle and develop (Thorson, 1966; Rogers, 1990). Herrnkind et al. (1988) suggested that large-scale siltation resulting from dredging, mineral mining, and other human activities must be viewed as potentially deleterious to spiny lobster recruitment.

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

7.5.2 Recolonization Periods 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. 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 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 (MacArthur, 1960; MacArthur and Wilson, 1967; Odum, 1969; Pianka, 1970; Grassle and Grassle, 1974).

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 periods 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 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. 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 loss of sediment stirring and aeration and may be followed by a build-up of organic matter (eutrophication) in 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 that have complex biological interactions with one another.

7.5.2.3 Recolonization Periods

The rate of recolonization is dependent on numerous physical and biological factors and their interactions. Physical factors include time of year, dredging technologies and techniques, borrow site dimensions, water currents, water quality, sediment composition, bedload transport, temperature, 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). Spatial and temporal variability in physical conditions may in some cases exert more influence on initial stages of recolonization than biological responses of species considered to be opportunists (Zajac and Whitlatch, 1982).

Biological factors influencing the rate of recolonization include the size of the pool of available colonists (Bonsdorff, 1983; Hall, 1994) and life history characteristics of colonizing species (Whitlatch et al., 1998). Recolonization of borrow sites may occur by transport of eggs, larvae, juveniles, and adults from neighboring populations by currents, 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. 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, 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.

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 1 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 1 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.

Recolonization of a borrow site was studied 3 km offshore of Great Egg Harbor Inlet near Ocean City, New Jersey (Scott and Kelley. 1998). Macrobenthic organisms were able to colonize the borrow site rapidly. Approximately 2 years after the last dredging, the number of taxa, diversity, and abundance in the borrow site recovered to conditions that existed in other borrow sites and undisturbed areas before dredging. The community composition within the borrow site may have changed, although the community change was described as not significant and not a result of dredging because the community composition of the borrow site was similar to the composition observed at the adjacent stations. Good juvenile surf clam recruitment occurred in the borrow site, but the population may not have reached size levels in nearby undisturbed sites 2 years after the last dredging. Although biomass and size of surf clams appeared diminished, there was no indication that the population would not stabilize given additional time. As dredging events were conducted in all seasons and no apparent effect was detected, no changes in the timing of dredging appeared to be necessary (Scott and Kelley, 1998).

Recolonization also was studied by Burlas et al. (2001) at borrow areas near Sites H1 and H2. Similar to the present study, their borrow areas were bathymetric high points on the seascape with strong currents and sand movement. Burlas et al. (2001) summarized their results by stating that abundance, biomass, richness, and the average size of the biomass dominant, which was the sand dollar *Echinarachnius parma,* declined immediately after dredging. Abundance, biomass, and richness recovered quickly after the first dredging operation with no detectable difference between dredged and undisturbed areas by the following spring. Abundance also recovered quickly after a second dredging operation, but biomass and richness were still reduced the next spring. Species and biomass composition were altered in similar manners by each operation. Immediately after dredging, the relative contribution of echinoderm biomass declined and the abundance of the spionid polychaete *Spiophanes bombyx* increased. Changes in biomass composition were longer lasting with the assemblage taking 1.5 to 2.5 years to return to undredged conditions.

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 differences among 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 (Saloman et al., 1982; Jutte et al., 2002) for shallow dredging to possibly decades for deep pits (Barry A. Vittor & Associates, Inc., 1999). Although abundance and diversity of benthic infauna within borrow sites often returned to levels comparable to pre-dredging or reference conditions within less than 1 year, several studies documented changes in benthic species composition that lasted much longer, particularly where sediment composition was altered (e.g., Saloman, 1974; Wright, 1977; 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: 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.), some previous studies tend to indicate that recovery of borrow sites occurs in approximately 1 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 dredging impacts and borrow site recolonization and recovery 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 literature on recolonization periods and success in borrow sites concerns infauna, some information exists for soft bottom epifauna. Numbers of taxa and individuals collected by trawls in a borrow site off Duval County, Florida greatly exceeded 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).

In general, hard bottom species take longer to recolonize their respective habitats than soft bottom species. This is particularly true for large reef-building corals living at the extreme northern end of their distributional range (Courtenay et al., 1972). When a reef community is destroyed, ecological conditions that follow cannot be expected to coincide with those that initially developed the community, and it cannot be assumed that the reef community will replace itself (Johannes, 1970 as cited by Levin, 1970). Connell (1997) cautioned about judging recovery of coral assemblages, in a similar way that Wilber and Stern (1992) did for soft bottom infaunal assemblages: recovery in coral abundance does not necessarily imply that the assemblage has recovered in several other characteristics, such as species composition, diversity, rates of reproduction and growth, colony size structure, etc. Recovery in abundance is only one aspect of recovery of a coral assemblage (Connell, 1997). Brown and Howard (1985) stated that generalizations concerning recolonization and recovery of reef corals are dangerous, and recommended consideration of each case individually. Because hard bottom species tend to be slow growing and direct mechanical damages to hard bottom habitats from dredging have occurred in the past (Courtenay et al., 1972, 1974; Britt & Associates, Inc., 1979; Marszalek, 1981; Blair and Flynn, 1988; Goldberg, 1989; Blair et al., 1990), surveys should be conducted in the future prior to dredging in and near specific borrow sites to determine if hard bottom is present and protective measures are necessary.

7.5.3 Predictions Relative to the Sand Resource Areas

7.5.3.1 Potential Soft Bottom Benthic Effects

Sediment Removal

The immediate impact of excavating upper sediments of a sand resource area will be removal of portions of the benthic invertebrate populations that inhabit shelf sediments, especially those fauna with sessile and slow-moving lifestyles. Surveys within and adjacent to the sand resource areas, as well as benthic investigations of nearby waters, reveal that benthic invertebrate assemblages of open shelf waters of the study area include crustaceans, echinoderms, mollusks, and polychaetous annelids.

The expected loss of benthic fauna due to sediment excavation could be considered to represent a negligible impact on the ecosystem when evaluating the impact on a broad spatial scale. Specific shoals within each sand resource area are targeted for excavation based on particular sedimentary and bathymetric characteristics. A significant extent of non-dredged areas will surround borrow sites. These undisturbed areas would be a primary source of colonizing fauna for the excavated site (Van Dolah et al., 1984; Jutte et al., 2002) 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 are expected to be localized and short-term.

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

It is possible that a change in surficial sediment composition 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 areas, 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 renourishment projects, and the volume of sand required.

Because the inner shelf ecosystem of the east Florida shelf exhibits some heterogeneity in sediment types and their associated infaunal assemblages, those assemblages that initially colonize dredged areas likely would be similar to some naturally occurring assemblages that inhabit nearby non-dredged areas, especially areas with finer sediments. When viewed within a context of scale, removal of sediments from portions of the inner 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 epibiota. Most epibiotal 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 epibiota inhabiting the study 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 restricted to the borrow areas. Most demersal populations exhibit naturally dynamic distributions and are distributed over a wide geographic area. However, there have been questions regarding the importance of shoal areas as orientation sites, staging areas, or aggregating sites for pelagic and demersal fishes (Research Planning, Inc. et al., 2001). Unfortunately, scientific data are lacking.

Most impacts of sediment removal on epibenthic and demersal fish taxa would be indirect in nature, through habitat alteration. A reduction of infaunal biomass resulting from sediment removal could have an indirect effect on 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 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 in dredged areas.

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 area. Seasonal variability should be considered when evaluating potential impacts due to sand removal. The timing of sand removal would seem to be less critical for minimizing the impact on 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 area 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. Central east Florida sand resource areas are characterized by a relatively limited amount of very fine sediments, indicating that the region encompassing those areas currently is not a depositional environment, but is hydrologically dynamic. In general, benthic assemblages of the inner central east Florida 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 epibiotal 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 at sites of initial redeposition because of the high-energy inner shelf environment. However, some low or depressional areas of the seafloor could receive 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.

Potential Recolonization Periods and Success

Germano (1999) has suggested that, despite all advances in theoretical ecology over the last half century and huge amounts of data that have been collected in various marine monitoring programs, we still do not know enough about how marine ecosystems function to be able to make valid predictions of impacts before they occur. The relative lack of understanding of complex ecological systems may in some cases even preclude our ability to observe significant negative environmental effects of activities of concern. However, review of previous studies does provide some evidence as to how certain activities, such as dredging, might affect benthic communities.

The period 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. 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 shallower cut over a much larger area.

Results of long-term environmental monitoring of a borrow site located 3.6 km offshore Coney Island, New York 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 (1995 through 1998) dredging. 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 to 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 non-dredged 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 its infaunal assemblage.

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. Central east Florida 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 (Camp et al., 1977; Lyons, 1989). 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 predredging infaunal assemblages within excavated sites depends in part on the length of time required for refilling of those mined areas. Shallow waters of the central east Florida inner shelf are strongly influenced by factors such as tidal currents, circulation, and storms. These same forces would tend to modify dredged sites toward predredging morphology. 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 the relatively shallow depths of the sand resource areas. The length of time required to reestablish infaunal assemblages also depends in large measure on the sediments exposed by dredging. Shoals tend to consist of well-sorted sands and be vertically uniform in sediment composition. Sediments exposed by dredging probably would not differ substantially from existing surficial sediments.

Assuming that the depth of sand excavation would not be so great as to substantially alter local hydrological characteristics, removal of benthic organisms along with sediments should quickly be followed by initial recolonization of dredged areas by opportunistic infaunal taxa. Early-stage succession tends to begin within days of sediment removal through settlement of larval recruits, primarily annelids and bivalves (Grassle and Grassle, 1974;

Simon and Dauer, 1977). Initial larval recruits likely would be dominated by populations of deposit feeding, opportunistic taxa, such as those collected from muddy sediment stations offshore central east Florida. These taxa may include polychaetes such as *Magelona* sp. H, *Mediomastus*, and *Paraprionospio pinnata*, and bivalves such as *Lucina* and *Tellina*. 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. Dredging of only a small portion of each sand resource area will ensure that a supply of non-transitional, motile taxa will be available for rapid migration into dredged areas.

Because sediment shoals in the central east Florida sand resource areas tend to be vertically uniform in terms of sediment composition, recolonization of exposed sediments by later successional stages likely will proceed even if dredged shoals are not completely reestablished, particularly if the depth of dredging does not cut below ambient grade. 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. Johnson and Nelson (1985) documented changes in benthos following excavation of a nearshore borrow site close to Fort Pierce Inlet. They found that relatively large reductions in abundance, but not number of species, occurred in the borrow site after dredging and that both parameters approximated predredging levels in from 9 to 12 months after the last dredging. Based on previous observations of infaunal reestablishment in dredged areas, the infaunal community in central east Florida offshore borrow sites most likely will become reestablished within 2 years, and will exhibit levels of infaunal abundance, diversity, and composition comparable to nearby nondredged areas.

7.5.3.2 Potential Hard Bottom Benthic Effects

Sediment Removal

Equipment used in the sediment removal process (e.g., cutterheads, dragheads, cables, anchors, pipelines, etc.) can physically damage hard bottom areas occurring close to sand borrow sites. For the sand resource areas studied in this report, hard bottom was documented in Areas B1, D1, D2, and near C2. Epibiotal assemblages observed on the hard bottom in and around Area D2 supported large sponges and octocorals that could be easily sheared off by mishandled anchor cables. Similar damage could occur to lower profile organisms (algae, small sponges, hydrozoans) characteristic of hard bottom assemblages in or near the other sand resource areas. Anchors and cutterheads could damage hard bottom structures that provide substrate for epibiota and fishes. Such impacts can be avoided by conducting hard bottom surveys prior to dredging. If hard bottom is found, detailed maps can be used in conjunction with precise positioning of all mechanical components that could potentially impact the seafloor.

Sediment Suspension/Dispersion

Suspended sediment affects sessile epibiota by interrupting photosynthesis in algae and organisms with symbiotic algae (e.g., some octocorals and scleractinian corals). High suspended sediment also can affect respiration causing metabolic stress in hard corals and other epibiota. Effects of turbidity generated in local areas will depend on background turbidity levels and therefore levels normally experienced by organisms composing local hard bottom assemblages. Because of the narrowness of the continental shelf and proximity of the Gulf Stream current, water clarity is consistently high in the southern portion of the study area. Epibiota on hard bottom outcrops in and around Areas D1 and D2 are expected to be least adapted to turbid water when compared to epibiota in and around the other sand resource areas where background turbidity is generally higher. Turbidity excess generated during dredging projects should be of short duration (acute) and restricted to small areas relative to the regional continental shelf. Chronic resuspension could occur in areas where deposits of fine sediments are exposed to waves and currents by dredging projects.

Sediment Deposition

High levels of sedimentation can impact hard bottom organisms by burying them, thereby preventing photosynthesis by algae, seagrasses, and coral zooxanthellae; clogging filter-feeding organisms such as sponges; or causing octocorals and scleractinian corals to bleach or expend large amounts of energy producing mucous to clear sediment from their surfaces. High sedimentation also can reduce recruitment of hard bottom organisms by covering potential substrate and burying newly settled juveniles. Sedimentation effects on hard bottom habitats in and around the sand resource areas will depend on sediment composition; distance from the dredging site to hard bottom areas; and prevailing tides, currents, wind, and local weather conditions. Dredge-related sediment deposition should be confined to areas close to the actual excavation points, thus avoiding hard bottom areas through pre-project surveys.

Potential Recolonization Periods and Success

Physical damage to hard bottom areas may occur through accidental contact of dredging equipment. Recolonization of a damaged hard bottom area within or near any of the sand resource areas off central east Florida would depend on the spatial extent of the damage, timing with respect to larval availability, latitudinal location of the damaged area, and composition of the impacted epibiotal assemblage.

Hard bottom assemblages in the vicinity of the sand resource areas are composed of algae, sponges, octocorals, hydrozoans, scleractinian corals, and other sessile organisms. Most members of these groups colonize disturbed or newly open hard bottom areas by settlement of planktonic larvae. Thus, the assembly of organisms on newly exposed hard bottom areas can be highly variable and depend on life history characteristics of individual species coupled with local circulation patterns. Because of spatial and temporal variation in these biotic and physical factors, colonization of impacted hard bottom may not follow the orderly successional process described in Section 7.5.2.2 for infauna. Timing relative to larval availability (spawning times) is a key aspect of hard bottom colonization that sets the starting point of species assembly. Recovery of hard bottom assemblages consisting of large sponges, octocorals, and scleractinian corals can take years or decades (Fizhardinge and Bailey-Brock, 1989). Recovery of scleractinian corals on damaged coral reefs takes years and in some cases decades and depends on the type of disturbance, coral species, ecological setting, and other factors (Connell, 1997).

If an area composed of large sponges and octocorals near the southern sand resource areas (particularly Area D2) was damaged, recovery would likely take years and possibly decades. A similar sized area covered mostly by algae and encrusting sponges such as those observed in sand resource areas north of Area D2 would likely recover more rapidly because algae and encrusting sponges grow rapidly and are adapted to conditions where space is limited and sediment movement is dynamic (Renaud et al., 1997).

7.6 PELAGIC ENVIRONMENT

7.6.1 Fishes

Potential impact producing factors from dredging operations in the sand resource areas that may affect pelagic fishes offshore of central east Florida include physical injury, attraction, and turbidity. These factors along with potential impacts are described in following subsections. Project scheduling considerations and essential fish habitat also are discussed in separate subsections.

7.6.1.1 Physical Injury

Physical injury through entrainment of adult fishes by hydraulic dredging has been reported for several projects (Larson and Moehl, 1988; McGraw and Armstrong, 1988; Reine et al., 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 of Florida 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.

7.6.1.2 Attraction

Even though dredges are temporary structures, they can still attract roving pelagic fishes. This attraction would be similar to an artificial reef effect, where both small and large coastal pelagic fishes become associated with fixed structures. This may temporarily disrupt migratory routes for some members of the stock, but it is unlikely that there would be an appreciable negative effect.

7.6.1.3 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, and when turbidity reduces light penetration, the fishes reactive distance decreases (Vinyard and O' Brien, 1976). Light scattering caused by suspended sediment also can affect a visual predator's ability to perceive and capture prey (Benfield and Minello, 1996). Some fishes have demonstrated the ability to capture prey at various turbidity levels, but the density of prey and light penetration are important factors (Grecay and Targett, 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 abraded and 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). High concentrations of fine sediments can coat respiratory surfaces of the gills, preventing gas exchange (Wilber and Clarke, 2001).

Understanding and predicting effects of suspended sediments on fishes requires some information on the range and variation of turbidity levels found at a project site prior to dredging (Wilber and Clarke, 2001). The spatial and temporal extents of turbidity plumes from either cutterhead or hopper dredges are expected to be limited. Therefore, there should be negligible impact on adult pelagic fishes. However, removal of coarse sediment from borrow sites could promote chronic turbidity if finer underlying sedimentary layers are exposed and resuspended.

7.6.1.4 Underwater Noise

Noise associated with all aspects of the dredging process may affect organisms in several ways. Some reef fish larvae have been shown to respond to sound stimuli as a sensory que to settlement sites (Stobutzki and Bellwood, 1998; Tolimieri et al., 2000). Alterations of background noise could impair the ability of newly settled fishes to locate preferred substrate. Changes in noise levels also may affect feeding or reproductive activities of reef fishes that depend on sound for these activities (Myrberg and Fuiman, 2002). Continental Shelf Associates, Inc. (2004) reviewed effects of noise on fishes. This report stated that all fish species investigated can hear, with varying degrees of sensitivity, within the frequency range of sound produced by cutterhead dredges, hopper dredges, and clamshell excavators. These sounds can mask the sounds normally used by fishes in their normal acoustic behaviors at levels as low as 60 to 80 dB (just above detection thresholds for many species). Levels as high as 160 dB may cause receiving fish to change their behaviors and movements that may temporarily affect the usual distribution of animals and commercial fishing. Continuous, long-term exposure to levels above 180 dB has been shown to cause damage to the hair cells of the ears of some fishes under some circumstances. These effects may not be permanent because damaged hair cells are repaired and/or regenerated in fishes. None of the dredge types proposed for this project produce continuous sounds above 120 dB (Richardson et al., 1995). Due to the short duration of most dredging projects, the effects of underwater noise on fish populations should be minimal.

7.6.1.5 Project Scheduling Considerations

It is uncertain whether hydraulic dredging will present a significant problem for pelagic fishes offshore of central east Florida or not. Temporal scheduling of environmental windows as means to avoid impacts is practical if the organisms in question are highly concentrated in an area during some specific time period. The only current window was established to protect nesting sea turtles. This window allows beach nourishment projects to operate from November to March, a time period when Spanish mackerel migrate into the study area to overwinter. If a project was conducted in the vicinity of an important gathering area for Spanish mackerel, there could be some temporary impact. Unfortunately, quantitative data are lacking to support the use of an environmental window to lessen effects on pelagic fishes.

7.6.1.6 Essential Fish Habitat

The Magnuson-Stevens Fishery Conservation and Management Act (16 United States Code [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 were made. One change was to charge the NMFS with designating and conserving Essential Fish Habitat (EFH) for species managed under existing FMPs. This is 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 Federal Register 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 SAFMC has produced several FMPs for single and mixed groups of species. All of these FMPs were recently amended in a single document (SAFMC, 1998a) to address EFH for shrimps; spiny lobster; golden crab; corals, coral reefs, and hard/live bottom; red drum; snapper-grouper management unit; and coastal pelagic fishes. In addition to the FMPs prepared by the SAFMC, highly migratory species are managed by the Highly Migratory Species Management Unit, Office of Sustainable Fisheries, NMFS. One FMP was recently prepared for highly migratory species that includes descriptions of EFH for sharks, tunas, and swordfish (NMFS, 1999a); a second FMP for Atlantic billfishes was amended to include EFH designations (NMFS, 1999b). Two additional highly migratory species, dolphin and wahoo, will soon be formally managed by the SAFMC, and an FMP is in progress. A separate FMP describing EFH for pelagic *Sargassum* in the South Atlantic was prepared in late 1998 (SAFMC, 2002).

Within the EFH designated for various species, particular areas termed Habitat Areas of Particular Concern (HAPCs) also are identified. HAPCs either play important roles in the life history (e.g., spawning areas) of Federally managed fish species or are especially vulnerable to degradation from fishing or other human activities. In many cases, HAPCs represent areas where detailed information is available on the structure and function within the larger EFH. Descriptions of EFH and HAPCs follow for the aforementioned FMPs and key managed species present in the study area. Some of these species also are “aquatic resources of national importance” under Section 906(e)(1) of the Water Resources

Development Act of 1986, and Part IV, Section 3(a) of the current Memorandum of Agreement between the Department of Commerce and USACE.

Penaeid and Rock Shrimps

EFH for penaeid shrimps includes inshore nursery areas such as tidal freshwater, estuarine, and marine wetlands (Table 7-1). Offshore sedimentary habitats where spawning and growth to maturity take place are important as EFH.

Table 7-1. Managed invertebrate and reef fish species for which Essential Fish Habitat has been identified off central east Florida (From: South Atlantic Fishery Management Council, 1998b). Organisms are listed in phylogenetic order.

Species	**Life Stages (Reproductive Activity)**	**Habitat**
Invertebrates		
Rock shrimp (*Syconia* spp.)	Adults; juveniles; larvae	Soft bottom (18 to 180 m); pelagic
Pink shrimp (*Farfantepenaeus duorarum*)	Adults; juveniles; larvae	Soft bottom, seagrass areas; pelagic
Spiny lobster (*Panulirus argus*)	Adults; juveniles; larvae	Hard bottom; seagrass areas, mangrove areas, sponges, macroalgae; pelagic
Golden crab (*Chaceon fenneri*)	Adults; larvae	Soft bottom (>200 m); pelagic
Reef Fishes		
Red grouper (*Epinephelus morio*)	Adults; juveniles; larvae; eggs	Hard bottom; seagrass areas; pelagic
Snowy grouper (*Epinephelus niveatus*)	Adults; juveniles; larvae; eggs	Hard bottom; pelagic
Black grouper (*Mycteroperca bonaci*)	Adults; juveniles; larvae; eggs	Hard bottom; seagrass areas; pelagic
Gag (*Mycteroperca microlepis*)	Adults; juveniles; larvae; eggs	Hard bottom; seagrass areas; pelagic
Scamp (*Mycteroperca phenax*)	Adults; juveniles; larvae; eggs	Hard bottom; pelagic
Mutton snapper (*Lutjanus analis*)	Adults; juveniles; larvae; eggs	Hard bottom; seagrass areas; pelagic
Gray snapper (*Lutjanus griseus*)	Adults; juveniles; larvae; eggs	Hard bottom; seagrass areas; mangrove areas; pelagic
Red snapper (*Lutjanus campechanus*)	Adults; juveniles; larvae; eggs	Hard and soft bottom shelf waters; pelagic
Lane snapper (*Lutjanus synagris*)	Adults; juveniles; larvae; eggs	Hard bottom; seagrass areas; pelagic
Vermilion snapper (*Rhomboplites aurorubens*)	Adults; juveniles; larvae; eggs	Hard bottom; pelagic
Yellowtail snapper (*Ocyurus chrysurus*)	Adults; juveniles; larvae; eggs	Hard bottom; seagrass areas; pelagic
Tilefish (*Lopholatilus chamaeleonticeps*)	Adults; juveniles; larvae; eggs	Soft bottom; pelagic
Greater amberjack (*Seriola dumerili*)	Adults; juveniles; larvae; eggs	Hard bottom; *Sargassum*; pelagic
Almaco jack (*Seriola rivoliana*)	Adults; juveniles; larvae; eggs	Hard bottom; *Sargassum*; pelagic
Gray triggerfish (*Balistes capriscus*)	Adults; juveniles; larvae; eggs	Hard bottom; *Sargassum*; pelagic

Rock shrimp EFH is composed of offshore terrigeneous and biogenic sedimentary bottoms in water depths ranging from 18 to 182 m deep, with maximum occurrence and abundance of organisms between 34 and 55 m (Table 7-1). EFH includes the water current transport system near Cape Canaveral, Florida, which is important in the retention and inshore transport of larval rock shrimp. The Gulf Stream also is considered an important larval transport mechanism (SAFMC, 1998b).

Areas considered to be HAPCs for penaeid shrimps include all coastal inlets, all State-designated nursery habitats, and State-identified overwintering areas.

Because rock shrimps are found generally in waters deeper than the sand resource areas, impacts to EFH will be minimal. The EFH for penaeid shrimps could be affected by dredging projects; entrainment and turbidity may be factors in the vicinity of Areas A1 and A2. However, due to the small areal coverage of these sand resource areas, effects are expected to be minimal.

Spiny Lobster

Spiny lobster EFH consists of hard bottom, coral reefs, crevices, cracks, and other structured bottom in shelf waters (Table 7-1). Juvenile habitat is in nearshore waters and ranges in type from massive sponges, mangrove roots, and seagrass meadows to soft bottom with macroalgal clumps. The Gulf Stream provides an important mode of transport for early life history stages of the spiny lobster (SAFMC, 1998b).

All HAPCs for spiny lobster are located south of the sand resource areas and include the Dry Tortugas, Florida Keys, and hard bottom from Fowey Rocks near Miami to Jupiter Inlet.

Spiny lobster EFH exists in all hard bottom areas throughout the study area. Measures should be taken to protect hard bottom areas and avoid dredging impacts to spiny lobster.

Golden Crab

Table 7-1 indicates the EFH for golden crab in the central east Florida region. Golden crab EFH includes a variety of bottom types, including foraminiferan ooze, distinct mounds of dead corals, ripple bottom, dunes, black pebbles, low outcrop, and soft bioturbated bottom (SAFMC, 1998b). All of these habitats are in water depths exceeding 200 m. The Gulf Stream is considered to be important in dispersal of planktonic eggs and larvae.

There is not enough information available on the ecology of golden crab from which to identify HAPCs.

Golden crab EFH occurs in water depths much greater than the depths of the sand resource areas, and therefore no impacts are expected.

Corals, Coral Reefs, and Hard/Live Bottom

EFH for reef building stony corals is outside of the study area and extends from Palm Beach County, Florida south through the Florida reef tract bordering the Florida Keys. This area extends from nearshore (0 to 4 m) to 30 m water depths where salinity is consistently above 30 ppt and water temperatures range from 15ºC to 35ºC. Corals, coral reefs, and hard/live bottom habitats were not included in the EFH tables.

EFH for *Antipatharia* (black corals) includes hard, exposed, rough, stable substrate throughout the management area in high salinity (30 to 35 ppt) offshore waters and depths exceeding 18 m not restricted by light penetration.

EFH for octocorals, except the order Pennatulacea (sea pansies and sea pens), includes hard, exposed, rough, stable substrate throughout the management area in subtidal to outer shelf depths within a wide range of salinity and light penetration.

EFH for Pennatulacea (sea pansies and sea pens) includes muddy, silty bottoms in subtidal to outer shelf depths within a wide range of salinity and light penetration.

HAPCs for corals, coral reefs, and hard/live bottom habitats of central east Florida include 1) *Phragmatopoma* worm reefs in nearshore waters; 2) nearshore hard bottom in water depths of 0 to 4 m; 3) offshore hard bottom in water depths of 5 to 30 m; and 4) *Oculina* banks from Fort Pierce to Cape Canaveral in water depths >30 m. Only the third category occurs in the study area.

Measures should be taken to avoid hard bottom and associated dredging effects to corals, coral reefs, and hard/live bottom. Dredging operations causing mechanical damage or producing high turbidity and sedimentation could significantly affect corals attached to hard bottom areas within the study area. Hard bottom was found in Areas B1, D1, and D2 and near C2 during field surveys. Mechanical damage to hard bottom in all sand resource areas should be avoided. Areas D1 and D2 would be most susceptible to elevated turbidity and sediment deposition because organisms in these areas are less adapted to these stressors. See Section 7.5.1 for discussion of impacts to corals.

Red Drum

EFH for red drum includes artificial reefs, estuarine emergent vegetated wetlands (flooded brackish marsh, mangrove fringe, flooded salt marshes, and tidal creeks), high salinity coastal areas, oyster reefs, submerged rooted aquatic vegetation (seagrasses), tidal freshwater, and unconsolidated bottom (Table 7-2). These habitats occur from Virginia to the Florida Keys (SAFMC, 1998b).

HAPCs for red drum are all State-designated nursery habitats of particular importance to red drum, coastal inlets, documented sites of spawning aggregations, and habitats for submerged aquatic vegetation (SAFMC, 1998b).

EFH for red drum exists mostly in inshore waters well isolated from the sand resource areas. For this reason, effects to red drum EFH are expected to be minimal.

Table 7-2. Managed species (red drum and coastal pelagic fishes) for which Essential Fish Habitat has been identified off central east Florida (From: South Atlantic Fishery Management Council, 1998b). Fishes are listed in phylogenetic order.

Species	Life Stages (Reproductive Activity)	Habitat
Red Drum		
Red drum (*Sciaenops ocellatus*)	Adults; larvae and eggs (spawning area)	Soft bottom; seagrass areas; oyster reefs; mangrove areas; wetlands; pelagic
Coastal Pelagic Fishes		
Cobia (*Rachycentron canadum*)	Adults; juveniles/subadults; larvae; eggs	Pelagic; hard bottom areas
Dolphin (*Coryphaena hippurus*)	Adults; juveniles/subadults; larvae and eggs (spawning area)	Pelagic; *Sargassum* mats
King mackerel (*Scomberomorus cavalla*)	Adults; juveniles/subadults; larvae and eggs (spawning area)	Pelagic; hard bottom areas
Spanish mackerel (*Scomberomorus maculatus*)	Adults; juveniles/subadults; larvae; eggs	Pelagic; hard bottom areas
Little tunny (*Euthynnus alletteratus*)	Adults; juveniles/subadults; larvae and eggs (spawning area)	Pelagic; hard bottom areas

Snapper-Grouper Management Unit

The snapper-grouper management unit is composed of 73 species from 10 families. Only the most important species of snappers, groupers, jacks, tilefishes, and triggerfishes are listed in Table 7-1. Families not listed in Table 7-1 are grunts, porgies, spadefishes, temperate basses, and wrasses. EFH for adults of this species group consists of hard bottom features such as artificial reefs, coral reefs, live bottom, and rocky outcrops (SAFMC, 1998b).

These features extend from nearshore out to at least 200 m water depths. Juveniles of many species utilize either hard bottom features or inshore habitats, including artificial structures (i.e., dock and bridge pilings), mangrove roots, oyster reefs, and seagrass meadows. Eggs and larvae of reef fishes are pelagic and reside in the upper water column for the first 20 to 50 days of life.

HAPCs described for the snapper-grouper management unit include high relief offshore areas where spawning occurs, localities of known spawning aggregations, and nearshore hard bottom areas. The SAFMC has proposed HAPCs in the study area including “The Pines” area off Sebastian (near Areas B1 and B2) and the “Hobe Sound Bar” off Hobe Sound (near Areas C2 and D1).

Snapper-grouper EFH exists on all hard bottom areas throughout the study area; therefore, effects of attraction, entrainment, and turbidity are possible. Measures should be taken to protect hard bottom areas and avoid dredging effects to snapper-grouper.

Coastal Pelagic Fishes

All members of the coastal pelagic management unit occur in central east Florida waters. Species most important to regional fisheries are cobia, dolphin, king and Spanish mackerels, and little tunny. Coastal pelagic species are migratory water column dwellers; however, most species have some affinity for manmade or natural structures. Hard bottom features, sandy bottoms, and shoal areas occurring from the surf zone to the shelf break encompass EFH for coastal pelagic fishes. Coastal inlets, high-salinity bays, and *Sargassum* rafts also are important for various life stages of coastal pelagic fishes. A species account of EFH for these species in central east Florida is given in Table 7-2.

EFH for coastal pelagic fishes could be affected by turbidity that could alter migratory routes or temporarily disrupt feeding activity in shelf or nearshore waters. Coastal pelagic species such as cobia, jacks, king and Spanish mackerels, round scad, and Spanish sardine could be attracted to a dredge and its attendant structures. Although these effects could occur, the small spatial and temporal scales of individual projects make these effects negligible.

Highly Migratory Species

Many highly migratory species are caught in the fisheries of central east Florida because of the proximity of the Gulf Stream to shore. Table 7-3 lists the billfishes, dolphin, sharks, swordfish, tunas, and wahoo with EFH in the central east Florida study area. For many of these fishes, species-specific information is limited. Blue and white marlins occur off central east Florida. Several shark species also frequent Gulf Stream, shelf, and in the case of the bull shark, estuarine waters of the region. *Sargassum* is important habitat for various life stages of swordfish and tunas. Swordfish and bluefin tuna migrate through the Florida Straits and into the eastern Gulf of Mexico to spawn (NMFS, 1999a). From an analysis of oceanic longline catch records, Worm et al. (2003) found the oceanic waters off east Florida to be “diversity hotspots” for highly migratory species.

HAPCs have not been designated by NMFS (1999ab) for members of the highly migratory species groups.

As with coastal pelagic fishes, highly migratory species could be affected by turbidity generated during a dredging project. Turbidity plumes could alter normal migratory and feeding patterns, but these effects would be of short duration. Some highly migratory species could be attracted to a dredge or related structures. These effects would be most important in the southern portion of the study area where the Gulf Stream current flows closer to shore.

Table 7-3. Managed highly migratory species for which Essential Fish Habitat has been identified off central east Florida (National Marine Fisheries Service, 1999a, b). Fishes are listed in phylogenetic order.

Species	Life Stages (Reproductive Activity)	Habitat
Sharks		
Nurse shark (*Ginglymostoma cirratum*)	Adults; late juvenile/subadult; neonates/early juveniles	Pelagic; hard bottom areas
Longfin mako shark (*Isurus paucus*)	Adults; late juvenile/subadult; neonates/early juveniles	Pelagic
Oceanic whitetip shark (*Carcharhinus longimanus*)	Late juvenile/subadult	
Spinner shark (*Carcharhinus brevipinna*)	Adults; late juvenile/subadult; neonates/early juveniles	Pelagic
Silky shark (*Carcharhinus falciformis*)	Adults; late juvenile/subadult; neonates/early juveniles	Pelagic
Bull shark (*Carcharhinus leucas*)	Adults; late juvenile/subadult; neonates/early juveniles	Pelagic; bays and estuaries
Night shark (*Carcharhinus signatus*)	Adults; late juvenile/subadult; neonates/early juveniles	Pelagic
Dusky shark (*Carcharhinus obscurus*)	Neonates/early juveniles	Pelagic
Caribbean reef shark (*Carcharhinus perezi*)	Adult; late juveniles/subadults	Pelagic
Sandbar shark (*Carcharhinus plumbeus*)	Adults; late juvenile/subadult; neonates/early juveniles	Pelagic
Tiger shark (*Galeocerdo cuvier*)	Adults; late juvenile/subadult; neonates/early juveniles	Pelagic
Lemon shark (*Negaprion brevirostris*)	Adults; late juvenile/subadult; neonates/early juveniles	Pelagic
Scalloped hammerhead (*Sphyrna lewini*)	Adults; late juvenile/subadults	Pelagic
Great hammerhead (*Sphyrna mokarran*)	Adults; late juvenile/subadults	Pelagic
Bonnethead (*Sphyrna tiburo*)	Adults; late juvenile/subadult; neonates/early juveniles	Pelagic
Tunas and Mackerels		
Wahoo (*Acanthocybium solanderi**)	Adults; juveniles and subadults; larvae and eggs (spawning area)	Pelagic
Skipjack tuna (*Katsuwonus pelamis*)	Adults; larvae and eggs (spawning area)	Pelagic; *Sargassum*
Yellowfin tuna (*Thunnus albacares*)	Adults; juveniles/subadults; larvae and eggs (spawning area)	Pelagic; *Sargassum*
Bluefin tuna (*Thunnus thynnus*)	Adults; larvae and eggs (spawning area)	Pelagic; *Sargassum*
Swordfish		
Swordfish (*Xiphias gladius*)	Adults; larvae and eggs (spawning area)	Pelagic
Billfishes		
Blue marlin (*Makaira nigricans*)	Adults; juveniles and subadults; larvae and eggs	Pelagic
White marlin (*Tetrapterus albidus*)	Adults; juveniles and subadults	Pelagic
Longbill spearfish (*Tetrapterus pfluegeri*)	Adults	Pelagic
Atlantic sailfish (*Istiophorus platypterus*)	Adults; juveniles and subadults; larvae and eggs (spawning area)	Pelagic

* Fishery Management Plan in progress.

Sargassum

Sargassum floats at the sea surface, often forming large mats. These accumulations attract numerous small fishes and invertebrates that become mobile epipelagic assemblages. Larger fishes, particularly billfishes, dolphin, tunas, and wahoo, associate with *Sargassum* mats in search of prey and possibly shelter (SAFMC, 2002). EFH for *Sargassum* is simply the shelf waters and Gulf Stream.

The Gulf Stream is considered an HAPC for drifting *Sargassum*.

Sargassum EFH encompasses much of the study area, particularly the south portion where the Gulf Stream is closest to shore. Effects on the drifting *Sargassum* assemblage are expected to be minimal.

7.6.2 Sea Turtles

Potential impact producing factors from dredging operations in the sand resource areas that may affect sea turtles offshore of central east Florida include physical injury, habitat loss or modification, turbidity, hypoxia/anoxia, and underwater noise. These factors along with potential impacts are described in following subsections. Project scheduling considerations also are discussed.

7.6.2.1 Physical Injury

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; NMFS, 1996, 1997). 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. 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, 1999b).

Of the five turtle species that may occur off Florida, 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). 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 depths of the sand resource areas. However, there also is risk in deeper water because when turtles feed there, they tend to stay on the bottom longer (NMFS, 1996).

Loggerheads are the most abundant turtles in the study area and historically 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 off Florida, 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 study area and tend to occur in the vicinity of hard bottom habitats. If a hopper dredge is used during the loggerhead turtle nesting season of April through September, the NMFS may require turtle monitoring and use of a turtle-deflecting draghead.

Based on the opinion of the NMFS (1996), the level of “take” (defined in this case as death or injury) resulting from physical injuries from the dredging operations is not likely to jeopardize the continued existence of any sea turtle species along Florida’s east coast.

7.6.2.2 Habitat Loss or Modification

Juvenile and subadult loggerhead, Kemp’s ridley, and green turtles use central east Florida inner shelf waters as developmental habitat, foraging on benthic organisms primarily on inner-shelf hard bottom habitats. 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). These effects would be temporary, as benthic populations within these soft bottom habitats would be expected to recover over a period of months to years, depending on the grain size and stability of subsurface sediments exposed after dredging (see Section 7.5.3). In addition, borrow sites represent only a small portion of this type of shallow benthic habitat available off east Florida.

7.6.2.3 Turbidity

Sea turtles in and near the study area may encounter turbid water that could temporarily interfere with feeding. However, due to the limited areal extent and transient occurrence of the sediment plume, turbidity is considered unlikely to significantly affect turtle behavior or survival.

7.6.2.4 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; Bartol et al., 1999), 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 sea 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 structures. 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.

7.6.2.5 Project Scheduling Considerations

Project scheduling, such as the implementation of environmental windows, is one way to avoid or reduce sea turtle impacts during dredging operations (Studt, 1987; Arnold, 1992; Dickerson et al., 1998; Reine et al., 1998; NRC, 2001). If a hopper dredge is used, then it would be best to avoid the loggerhead nesting season, which has been reported as April through September (Ryder et al., 1994). This same period would generally have higher risk of encountering juvenile and subadult green, Kemp's ridley, hawksbill, and leatherback turtles. 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 (requiring onboard observers), use of a turtle-deflecting draghead (NMFS, 1996), or relocation trawling. If a cutterhead suction dredge is used, seasonal or other restrictions are considered unnecessary because this procedure is considered not likely to adversely affect sea turtles by the NMFS (B. Hoffman, 2002, pers. comm., NMFS, St. Petersburg, FL).

7.6.3 Marine Mammals

Potential impact producing factors from dredging operations in the sand resource areas that may affect marine mammals offshore of central east Florida include physical injury, turbidity, and noise. These factors along with potential impacts are described in following subsections. Project scheduling considerations also are discussed.

7.6.3.1 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 (toothed) marine mammals most likely to be found in inner shelf waters off central east Florida, 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 two endangered species of mysticete (baleen) whales: the North Atlantic right 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). Manatees are uncommon to rare within offshore waters of the inner shelf. However, they are extremely vulnerable to vessel strikes within inshore waters from transiting vessels. Measures to minimize the potential for vessel strikes of endangered whales and manatees could be part of any Biological Opinion issued by the NMFS and USFWS for dredging off east Florida.

7.6.3.2 Turbidity

Marine mammals in and near the study 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.

7.6.3.3 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, mysticete (baleen) whales and especially manatees are more likely to be affected by low frequency noise than are odontocete marine mammals (Richardson et al., 1995; Gerstein et al., 1999). The main concern would be that dredging noise could cause avoidance of the dredging area during humpback whale and (especially) North Atlantic right whale migrations. It is presumed that any manatees in offshore waters near the dredging operation would avoid the source of noise.

7.6.3.4 Project Scheduling Considerations

Northern right whales occur as seasonal (winter and early spring) residents. Humpback whales could occur as occasional transients (strays), primarily during winter. Generally, the probability of encountering these species in the study area would be lowest during summer. The months of December through March would be least favorable because North Atlantic right whales typically reside in waters of the study area, particularly the northern part (Kraus et al., 1993; Slay et al., 1998). Whether or not environmental windows (seasonal restrictions on dredging) are implemented, measures to minimize possible vessel interactions with endangered whales are likely to be required by the NMFS. 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.

7.7 POTENTIAL CUMULATIVE EFFECTS

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.

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 for Areas A, B, and D. However, the proposed sites in Area C do have significant impacts to transport potential along the shoreline. Therefore, Area C sites should be redesigned so impacts are within acceptable limits, most likely by reducing the maximum depth of excavation at the sites.

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 central east Florida for beach replenishment. Primary concerns focused on physical and biological components of the environment at nine proposed sand resource areas. Physical processes and biological characterization 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. The following summary documents 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 were 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 offshore central east Florida, 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 was relatively straightforward, evaluating the significance of predicted changes for accepting or rejecting a borrow site was 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 offshore Cape Canaveral, Canaveral Shoals, the complex of ridges and troughs that extend southeast from Cape Canaveral, caused significant increases in wave height as waves propagated over this area. As 1.0 m, 7.7 sec waves from the east-southeast refracted around the shoals, wave heights increased by 0.5 m over offshore wave conditions. Significant changes in wave direction also were observed in these areas. A greater degree of wave refraction was illustrated for longer period waves. For a 1.6 m, 14.3 sec wave propagating from the east-northeast, wave direction for some nearshore regions adjacent to the Cape changed more than 45 degrees, following the gradient in bathymetric contours. Largest waves in the model domain occurred at shoals northeast of Port Canaveral (1.3 m higher than offshore waves). At shoals in the vicinity of the borrow site in Area A1, wave heights increased to a maximum of 2.8 m, 1.2 m above offshore conditions. Shoals tended to refract wave energy and caused focusing (wave convergence) near the Cape. However, the coast south of the Cape illustrated reduced wave heights (wave divergence).

Post-dredging wave height changes offshore Cape Canaveral illustrated a maximum wave height increase of 0.2 to 0.7 m and maximum wave height decrease in the shadow zone of the site of 0.3 m. The overall area of influence for the borrow site in Area A1 extended approximately 14 km north of the Cape to about 4 km south of Port Canaveral. The area of greatest wave height increase occurred at the northwest corner of the site. Wave heights did not increase by the same amount at the southwest corner, likely due to local bathymetry and geometry of the site. Deeper excavation depths at the northwest corner cause a greater degree of wave refraction. However, for all wave simulation cases, the impact of borrow site excavation on wave height and direction changes was minor relative to natural variability of the local wave climate and transport regime.

Wave model output for waves propagating from the NNE, offshore Sebastian Inlet at borrow sites in Areas B1 and B2, illustrated minor changes throughout the model domain. The shoal encompassing the borrow site in Area B1 had the greatest influence on wave propagation in the region, although effects were small because the shoal had a minimum depth of approximately 12 m NGVD. Changes in the wave field caused by dredging at borrow sites in Areas B1 and B2 illustrated minor impacts for the Area B model domain. For 1.9 m, 6.9 sec waves propagating from the NNE, borrow sites had a limited influence on waves over a long section of coast (>30 km), but changes on the order of 0.01 m occurred along 2.5 km of coast landward of the borrow site in Area B1. Maximum change in wave height was approximately 0.10 m at Area B1 and 0.12 m at the borrow site in Area B2. The length of shoreline influenced by changes in wave propagation for 1.7 m, 10.8 sec waves propagating from the north-northeast from the two borrow sites was approximately 20 km; however, greatest changes occurred within a 12 km stretch of coast. At Area B1, maximum changes in wave height were 0.13 m, very similar to those computed for the borrow site in Area B2. However, for all wave simulation cases offshore Sebastian Inlet, the impact of borrow site excavation on wave height and direction changes was minor relative to natural variability of the local wave climate and transport regime.

For the wave model domain offshore St. Lucie Inlet, 1.5 m, 7.5 sec waves propagating from the northeast illustrated slight wave focusing at shoals within the designated borrow site boundaries. The minimum depth at Site C1 north was 7.6 m NGVD, and 5.4 m NGVD was the minimum depth at Site C1 south. Because shallower depths exist in these areas, waves passing over the shoals refracted toward the shoreline sooner than in other areas the same distance offshore. For C1 north, maximum wave height increase was 0.18 m, and the maximum decrease was 0.39 m. Similar changes occurred at C1 south, where the maximum increase in wave height was 0.13 m and the maximum decrease was 0.33 m. For 1.1 m, 11.1 sec waves from the east, wave height changes at C1 north and C1 south were not as large as those for Case 2C, but wave energy was still focused behind the shoals. This focusing caused a zone of increased wave heights that extended to the shoreline.

For post-dredging conditions, wave height differences resulting from dredging Sites C1 north and C1 south indicated a strong interaction between the two sites because C1 south was partially within the shadow zone of C1 north. The alignment of borrow sites caused a single area of increased wave heights at the shoreline (approximately 4 km long) and a more diffuse zone of reduced wave heights (extending 12 km south toward St. Lucie Inlet). Similar results were found for longer period waves from the east, where wave height differences illustrated that the borrow sites have an overlapping influence at the shoreline, even though one site was not directly in the shadow of the other. For these longer period waves, the total length of affected shoreline was approximately 16 km, and changes at borrow sites were similar in magnitude to waves from the northeast.

The primary bathymetric feature impacting wave propagation in modeled Area D is located approximately 5.6 km offshore Jupiter Inlet. The shoal has a minimum water depth of 11.7 m NGVD, and the borrow site in and adjacent to Area D2 lies along the seaward margin of the shoal at the Federal-State boundary. For 1.4 m, 6.9 sec waves from the NNE, the shoal produced a slight focusing of waves seaward of the shoal and an area of reduced wave heights 2.6 km along the shoreline north of Jupiter Inlet. Similar results were documented for 1.3 m, 13.0 sec waves from the ENE. Wave heights increased behind the shoal, and a 4.9 km stretch of coastline north of Jupiter Inlet experienced increased wave heights.

Wave height changes resulting from dredging Borrow Site D2 showed greatest change at the north end of the site where the deepest excavation occurred. The maximum increase and decrease in wave height that resulted for waves from the north-northeast was 0.04 and 0.05 m, respectively. This small change relative to changes at borrow sites to the north was due to greater water depths at and seaward of the borrow site. Overall, wave simulation cases offshore Jupiter Inlet illustrated minor wave height and direction changes in response to borrow site excavation relative to natural variability of the local wave climate and transport regime.

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.

Circulation patterns along the central east Florida coast near potential offshore borrow sites were investigated using current meter observations obtained offshore St. Lucie Inlet and over Thomas Shoal, seaward of Sebastian Inlet. Analysis of historical data indicated that circulation patterns consisted predominantly of along-shelf currents that reversed direction approximately every 2 to 10 days. Current reversals were found weakly correlated with local wind stress; literature suggested that subtidal variability was due to meanders or spin-off eddies of the Florida Current. Peak speeds were on the order of 40 to 50 cm/sec at mid-shelf and inner-shelf locations and were directed either upshelf (to the north-northwest) or downshelf (to the south-southeast). Strongest currents were most commonly directed to the north. Tidal currents contributed significantly to inner-shelf current observations; however, these observations were obtained near the tidally-dominated St. Lucie Inlet and may not be reflective of inner shelf regions removed from major coastal inlets.

ADCP measurements in the vicinity of Thomas Shoal offshore Sebastian Inlet also were dominated by along-shelf flows that correlated with seasonal changes in wind. May survey conditions were dominated by winds from the south, while September survey conditions were characterized by short wind events from the north. Current measurements illustrated a mean flow directed to the north during spring and to the south in fall. This seasonal directionality of flow was supported by historical data and literature regarding observations on the mid-shelf and inner-shelf where sand resource areas have been identified. Strongest currents flowed to the south at 30 cm/sec during the September survey in response to northerly winds.

In shallow waters, over shoals and adjacent to tide-dominated inlets such as St. Lucie, cross-shelf tides may influence current velocities. May and September field data showed onshore currents dominated across the shoal. During the May survey, onshore currents were enhanced by flood tide. Tidal dependence was not observed during the September survey. On the inner- to mid-shelf, in the vicinity of the sand resource areas, tidal effects are secondary to wind effects. In the presence of local bathymetric features, such as Thomas Shoal, steering and sheltering of flow across the shoal were observed. Under average conditions, currents were steered onshore across the shoal. In the presence of dominant winds, near-bottom currents flowed parallel to bathymetric contours.

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 resulting dredging will not remove enough material to significantly alter major bathymetric features in the region. Therefore, the forces and/or geometric features that principally affect circulation patterns are expected to 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 1877/83 to 2002 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 bathymetric change documented four important trends relative to study objectives. First, the predominant direction of sediment transport on the continental shelf and along the outer coast between Cape Canaveral and Jupiter Inlet was north to south. The greatest amount of shoreline change in this study was associated with beaches adjacent to Cape Canaveral, Port Canaveral Entrance, and beaches south of St. Lucie Inlet. Second, the most dynamic features within the study area are the beaches and shoals associated with Cape Canaveral. Areas of significant erosion and accretion reflect wave and current dynamics and the contribution of littoral sand transport from the north to shoal and spit migration. Depositional zones also were prominent in the shoal regions along the inner shelf from Fort Pierce south to Jupiter Inlet. Large quantities of carbonate and shell fragments observed in sediment samples collected from shoals in this region indicated that much of the deposition in this portion of the study area may have been locally produced.

Third, alternating bands of erosion and accretion documented between 1956 and 1996 offshore Cape Canaveral illustrated steady reworking of the upper shelf surface as sand ridges migrated from north to south. The process by which this was occurring at Area A1 suggested that the borrow site in this region would fill with sand transported from the adjacent seafloor at rates ranging from 88,000 to 119,000 m^3/yr. Areas of erosion and accretion documented between 1929/31 and 1929/73 between Port Canaveral Entrance and Jupiter Inlet indicated the amount of sediment available for infilling sites south of Port Canaveral Entrance was between 38,000 and 113,000 m^3/yr.

Finally, net longshore transport rates determined from seafloor changes in the littoral zone between Cape Canaveral and Port Canaveral Entrance, in conjunction with dredging records for Port Canaveral entrance, indicated maximum transport rates near Cape Canaveral, with lower rates south of the entrance. Net longshore transport at Port Canaveral entrance was estimated at about 236,000 m^3/yr. South of the Port, rates have been estimated to range from 119,000 m^3/yr immediately south of the entrance to 140,000 to 184,000 m^3/yr between Fort Pierce and Jupiter Inlets.

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 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 borrow material during infilling will vary based on location, time of dredging, and storm characteristics following dredging episodes. Average computed infilling rates ranged from a minimum of about 5,000 m^3/yr (Site D2) to a high of about 538,000 m^3/yr (Site A1), while the infilling time varied from 25 to >500 years. Site A1 had the greatest infilling rate due to its shallow water depth relative to the other sites and its large perimeter. Because Site A1 is in shallow water, wave-induced and wind-driven currents were larger than at deeper sites, and more sediment was mobile in the proximity of the borrow site. Furthermore, sites that have a larger surface area generally trap more sediment in a given time period. Estimated infilling rates and times are most useful as a relative guide for borrow site infilling rather than an absolute indicator of exactly how long it takes for the borrow site to fill. The analysis performed provided a reasonable estimate of infilling times for resource management purposes.

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. The significance of changes to longshore transport along the modeled shoreline resulting from dredging proposed borrow sites to their maximum design depths was determined using the method described in Kelley et al. (2004).

Mean sediment transport potential calculated for the shoreline south of Port Canaveral indicated strong net southerly transport of approximately 500,000 m^3/yr, which gradually reduced to approximately 300,000 m^3/yr south of Indialantic Beach. The transport significance envelope was largest (approximately ±300,000 m^3/yr) north of Cape Canaveral and near Indialantic Beach. Model output for the region south of Cape Canaveral indicated that the significance envelope was approximately 20% of the mean computed net transport potential in the area of greatest impact from the borrow site in Area A1. The maximum modeled decrease in south-directed transport for post-dredging conditions was about a 40,000 m^3/yr (within the transport significance range), just south of Port Canaveral.

Mean transport potential computed adjacent to Sebastian Inlet indicated that net transport potential was generally less than 100,000 m^3/yr to the south, with an approximate ±500,000 m^3/yr range in net transport potential. Computations indicated that it was possible in some years for net transport potential to be northward directed. Near Vero Beach, net transport potential was to the south at around 500,000 m^3/yr and annual variation in net transport potential was similar (approximately ±500,000 m^3/yr). This may be due to a change in shoreline orientation that occurred at this point. The transport significance range for computed mean transport rates was nearly consistent at about ±100,000 m^3/yr. The largest calculated differences between existing and post-dredging transport potential occurred north of Sebastian Inlet (where the transport rate becomes more southerly by 30,000 m^3/yr) and just south of the inlet (where transport rates become less southerly by 30,000 m^3/yr), indicating that Sites B1 and B2 would not produce significant modifications to coastal processes along the shoreline.

Computed mean annual transport potential for the beaches just north of St. Lucie Inlet was to the south, ranging from approximately 400,000 m^3/yr at the northern extent of the grid to approximately 100,000 m^3/yr at the southern limit near St. Lucie Inlet. Annual variability in transport potential had a range of approximately ±400,000 m^3/yr to the north that gradually decreases to approximately ±200,000 m^3/yr at the southern limit of the modeled area. Along some sections of the modeled shoreline, it was possible to have net northerly-directed transport during some years. For Borrow Sites C1 north and C1 south (north of St. Lucie Inlet), the computed longshore transport significance range was approximately ±100,000 m^3/yr at the northern limit of the area and ±50,000 m^3/yr at the southern limit. Potential impacts from dredging these sites to a maximum excavation depth of 12 m NGVD indicated that the significance envelope was exceeded along a 2-km length of shoreline approximately 18 km north of St. Lucie Inlet. At the point of maximum dredging-induced change along the shoreline, the significance level was ±60,000 m^3/yr, and the computed change in transport potential was 85,000 m^3/yr. As such, the proposed borrow site configuration may not be acceptable. If a borrow site redesign were required, the most likely change would be a reduction in maximum dredging depth to reduce site impacts.

Net transport along the coastline adjacent to Jupiter Inlet varied from about 200,000 m^3/yr to the south near the northern limit of the area to about 500,000 m^3/yr to the south near Jupiter Inlet. Annual transport variability ranged from approximately ±150,000 m^3/yr in the northern part of the area to approximately ±300,000 m^3/yr at the southern extent of the model grid. As with the entire study area south of Cape Canaveral, net transport potential was always to the south and transport variability was large. The envelope of significant change in potential longshore transport rates under natural wave propagation conditions for Borrow Site D2 (offshore Jupiter Inlet) ranged from approximately ±50,000 m^3/yr in the north to ±100,000 m^3/yr in the south, with a maximum of approximately ±150,000 m^3/yr occurring just north of Jupiter Inlet. Modeled dredging impacts to transport potential for Site D2 were minimal; predicted changes were well within the transport variability significance range. Small impacts for this area (compared with previous modeled areas) resulted from larger borrow site depths, smaller excavation volume, and the sheltering effect of the shoal landward of D2.

Overall, it was determined that no significant changes in longshore sediment transport potential would result from modeled borrow site configurations for Areas A, B, and D. However, the proposed sites in Area C do have significant impacts to transport potential along the shoreline. Therefore, Area C sites should be redesigned so impacts are within acceptable limits, most likely by reducing the maximum depth of excavation at the sites.

8.3 BENTHIC ENVIRONMENT

Results of the biological field surveys agree well with previous descriptions concerning benthic assemblages associated with shallow areas offshore east Florida. 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, mollusks, and polychaetes. Canonical discriminant analysis indicated that the composition of infaunal assemblages was affected primarily by sediment type and secondarily by survey. Distributions were affected mostly by the amount of very fine sediments in benthic grabs, primarily silts and to a lesser degree clays. Very few infaunal taxa in this study were distributed across a broad sedimentary regime. Most species were restricted to stations with varied amounts of measurable fines, measurable gravel, or pure sand. Stations with measurable gravel yielded the greatest numbers of infauna. Species richness and individual abundance values were greater in September than June because of seasonal recruitment patterns. Between-survey differences at stations with measurable gravel were due primarily to the September presence of species that were largely or completely absent in June samples. Finer sediments, including sand stations and stations with measurable mud, had similar infaunal composition across surveys. Sand stations yielded burrowing amphipods during both field surveys. Between-survey differences at muddy sand stations were due to more abundant mud-dwelling infauna in September samples.

In addition to sedimentary habitat and survey month, discriminant analysis indicated that infaunal assemblage differences between stations were correlated somewhat with water depth. Shallowest stations in the study yielded similar assemblages. Deeper stations in Areas D1 and D2 were delineated as a group in the cluster analysis, despite differences with respect to sediments. The proximity of the Gulf Stream to the southern portion of the study area may have influenced the infaunal community in this area.

Epifauna consisted primarily of decapods. Sand dollars and squids also were prominent in trawls. During September, 90% of all epifaunal individuals were collected from Areas A1, A2, and A3. Epifaunal taxa were heterogeneously distributed during June, except for *E. michelini* and spider crab that were collected from multiple stations. These between-survey differences in epifaunal distribution are likely due to seasonal changes in water temperature, known to be a primary environmental regulator of the distributions of motile epifaunal populations.

Fishes collected by trawling in the nine sand resource areas reflected the transitional regional species pool of east-central Florida that includes a complex of tropical, subtropical, and warm temperate taxa. Although most species collected in the sand resource areas were typical soft bottom forms such as drums, flatfishes, and searobins, some hard bottom species were collected in Area D1. There were considerable differences in the composition, diversity, and numbers of fishes caught by trawling during the September and June surveys, particularly in northern Areas A1, A2, A3, and B1, reflecting seasonal trends in the occurrence and abundance of fishes in the South Atlantic Bight. Fishes collected were common members of the regional ichthyofauna, exhibiting expected spatial and temporal patterns in their distribution.

Effects of dredging on soft bottom fishes would include turbidity and disruption of benthic prey base utilized by many demersal species. Fishes are likely to avoid highly turbid areas and would respond in species-specific fashion to changes in the benthic invertebrate assemblages.

Potential benthic effects from dredging will result from sediment removal, suspension/dispersion, and deposition. Effects on infaunal populations primarily will occur 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 such as *Mediomastus* and *Paraprionospio pinnata* and bivalves such as *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 area, 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 nondredged 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.

Hard bottom habitat was surveyed and described in Areas B1, D1, and D2 and near C2. Epibiota and demersal fish assemblages associated with hard bottom were typical for the region. From a qualitative perspective, octocoral density and taxonomic richness was higher in the southern Areas D1 and D2 than the northern Areas B1 and C2 and algal cover was more prevalent in the northern areas. These trends indicate that natural environmental factors (water temperature, clarity, and circulation) influence the composition of epibiotal assemblages on a broad scale (kilometers) along the east coast of Florida. These observations suggest that epibiotal assemblages in the southern areas would take longer time to recover from mechanical impacts associated with sediment removal and would be more sensitive to sediment resuspension and deposition than would assemblages north of Areas D1 and D2.

8.4 PELAGIC ENVIRONMENT

Pelagic fishes such as bluefish, cobia, jack crevalle, and king and Spanish mackerels are important economically and ecologically in eastern Florida shelf waters and could be susceptible to impacts associated with dredging. Dredge-related turbidity can divert pelagic fishes from normal migratory routes, feeding grounds, or spawning areas. Structures and vessels may attract pelagic fishes for various reasons and in doing so also divert them from regular migratory routes. Noise from working dredges could affect pelagic fishes attracted to the structures. Despite the possibility of these effects on pelagic fishes, dredging at the central east Florida sand borrow sites is not likely to adversely affect pelagic fish populations unless specific spawning, aggregation, or migratory areas are disrupted. The limited spatial and temporal scale of dredging projects expected for the sand resource areas would lessen the severity of any potential effects.

Essential fish habitat for managed species occurring in the study area broadly includes the water column as well as soft and hard bottom substrates. Managed species or species groups occurring in the project area are penaeid and rock shrimps, golden crab, spiny lobster, corals, coral reefs, and hard/live bottom areas, red drum, coastal pelagic fishes, reef fishes (snapper-grouper management unit), highly migratory species, and *Sargassum*. Although some of these species or groups do not normally inhabit the sand resource areas, most of them will traverse the water column as planktonic early life stages. Dredging could affect small segments of the habitats and species in the sand resource areas through mechanical damage of hard bottom, sediment suspension and turbidity, and direct burial of organisms or habitats. The magnitude of these effects is generally expected to be small due to the relatively small spatial and temporal scales encompassed by dredging projects. Nevertheless, careful management of dredging operations should be undertaken to ensure that impacts from routine operations and accidents do not adversely impact EFH or managed species within the study area.

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. Of the five sea turtle species that typically occur off Florida (loggerhead, green, hawksbill, Kemp’s ridley, and leatherback), all except the leatherback are considered to be at risk because of their benthic feeding habits.

Loggerheads are the most abundant turtles in the study 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 operations during the period that corresponds with their nesting season inshore of the study area (April through September). This same period would generally have higher risk of encountering nesting green and hawksbill turtles and juvenile and subadult Kemp's ridley turtles. 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 and the unrestricted, open ocean environment where operations are planned. Northern right whales occur as seasonal residents during winter and spring (December through March). Humpbacks are only occasional strays from the main migrating population during winter months. Generally, the probability of encountering these species in the study area would be lowest during summer. It is then likely that seasonal restrictions on dredging and other measures to minimize possible vessel interactions with endangered whales may be required by the NMFS.

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