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Effects of Sand Mining on Physical Processes and Biological Communities Offshore New Jersey, U.S.A.

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ABSTRACT

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Physical processes and biological data were collected and analyzed for eight sand resource areas on the New Jersey Outer Continental Shelf to address environmental concerns raised by the potential for mining sand for beach replenishment. Nearshore wave and sediment transport patterns were modeled for existing and post-dredging conditions, with borrow site sand volumes ranging from 2.1 to 8.8×10^6 m^3. Wave transformation modeling indicated that minor changes will occur to wave fields under dominant directional conditions and selected sand extraction scenarios. Localized seafloor changes at borrow sites are expected to result in negligible impacts to the prevailing wave climate at the coast. At potential impact areas along the New Jersey coast, wave height changes averaged approximately ± 3 to 15% when compared with wave heights for existing conditions. For all selected sand borrow sites offshore New Jersey, average variation in annual littoral transport was approximately 10% of existing values. Because borrow site geometries and excavation depths are similar to natural ridge and swale topographic characteristics on the New Jersey OCS, infilling rates and sediment types are expected to reflect natural variations within sand resource areas.

Infaunal distribution and abundance correlated best with the relative percentages of gravel and sand in surficial sediments. In addition to sediment regime, other physical environmental differences between northern and southern portions of the study area also may have affected infaunal community patterns. Impacts to the benthic community are expected from physical removal of sediments and infauna. Based on previous studies, levels of infaunal abundance and diversity may recover within 1 to 3 years, but recovery of species composition may take longer. The nature and duration of benthic effects may differ with location of mined sites, due to physical and biological differences between northern and southern portions of the New Jersey shelf.

ADDITIONAL INDEX WORDS: *Bathymetric change, benthic, infauna, sediment transport, shoreline change, wave modeling.*

INTRODUCTION

Development of beaches for recreational purposes along the New Jersey coast started in the mid-1800s because of the attractive barrier island beaches and warm climate during summer. In addition, these beaches were near New York and Philadelphia metropolitan areas and accessible by boat, wagon, and rail (Quinn, 1977). The first beach developments were in Cape May, Long Branch, and Atlantic City (Wicker, 1951). Piers and boardwalks were built, along with shoreline protection structures to combat ocean wave forces at the coastline. Beach nourishment has been conducted since the 1950s at a number of vulnerable beach erosion hot spots to enhance recreation and protect upland areas from storm damage. The need for sand to replenish eroding beaches continues to concern local, State, and Federal resource agencies, prompting exploration and environmental evaluation of offshore sand resource areas for future use.

In recent years, there has been increasing interest in sand and gravel mining on the Outer Continental Shelf (OCS). The U.S. Department of the Interior, Minerals Management Service (MMS) has significant responsibilities with respect to potential environmental impacts of offshore sand and gravel mining. Existing regulations governing sand and gravel mining provide a framework for comprehensive environmental protection during operations. Guidelines for protecting the environment stem from a wide variety of laws, including the OCS Lands Act, National Environmental Policy Act, Endangered Species Act, Marine Mammal Protection Act, and others. Regulations require activities to be conducted in a manner which prevents or minimizes the likelihood of any occurrences that may cause damage to the environment.

This paper discusses some physical and benthic biological aspects of a study whose purpose and objectives were specified by the MMS. The study purpose was to address environmental concerns associated with potential sand mining operations at eight OCS sand resource areas offshore New Jersey for beach replenishment. Four objectives addressed the study purpose: 1) document potential modifications to waves due to offshore sand mining at selected borrow sites; 2) evaluate impacts of offshore sand mining relative to existing sediment transport patterns, sedimentary environments, and local shoreline processes; 3) characterize benthic ecological con-

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ditions in and around OCS sand resource areas using existing information and data collected from field surveys; and 4) evaluate infaunal assemblages and assess potential effects of offshore sand mining on these organisms, including an analysis of recolonization periods and success following dredging. Because monitoring surveys of actual sand mining operations were not to be conducted, the assessment of potential infaunal effects was based only on benthic infaunal characterization field surveys and existing literature. The paper focuses on physical and infaunal effects from sediment removal. It also provides statistical properties of local infaunal assemblages that will assist in designing future sand resource monitoring programs, which will set the stage for rigorous evaluations of post-mining conditions. Other potential impacts from sediment suspension/dispersion (turbidity) and deposition are addressed in BYRNES *et al.* (2000).

STUDY AREA

The inshore portion of the continental shelf, seaward of the Federal-State OCS boundary and within the Exclusive Economic Zone (EEZ), encompassed the study area from approximately 40°08′N latitude (Manasquan Inlet) to 38°55′N latitude (Cape May) (Figure 1). Although the Federal-State jurisdictional boundary marks the landward limit of the study area, the ultimate use of sand extracted from the OCS is for beach replenishment along the New Jersey coast. The seaward limit of the study area was within about 20 km of the shoreline. Sand resource areas were located between the 10- and 20-m depth contours. The continental shelf surface within the study area contains many morphologic features formed during the Holocene. Sand ridges 2 to 5 m high and 0.5 to 1.5 km apart were primary sand resource targets.

Eight sand resource areas were defined within the study area through a Federal-State cooperative agreement between the MMS and New Jersey Department of Environmental Protection (NJDEP), New Jersey Geological Survey (UPTEGROVE *et al.,* 1995). Seven borrow sites within Sand Resource Areas A1, A2, G1, G2, G3, C1, and F2 were defined to evaluate potential impacts of sand mining on wave and sediment transport processes (Figure 1). Sand Resource Area F1 was not included in the physical processes analysis because the quantity of sand was small ($<1 \times 10^6$ m^3) relative to beach replenishment needs, and water depths were greatest in this region, making potential dredging operations more complicated and costly.

REGIONAL SETTING

The outer coastline of New Jersey is approximately 210 km long and represents part of the passive, slowly subsiding, eastern North American continental margin (KLITGORD *et al.,* 1988; SMITH, 1996). Coastal features are represented by a series of barrier beaches and islands, punctuated by inlets that allow exchange of sediment and water between estuaries and the continental shelf (Figure 2), primarily as a function of tide.

Along the northern New Jersey coast, beaches formed at the base of Cretaceous, Tertiary, and Quaternary bluffs that extend up to 8 m above mean sea level (UPTEGROVE *et al.,* 1995). These eroding bluffs are the primary source of coastal sediment to adjacent beaches in northern New Jersey, where wave-generated longshore currents (CALDWELL, 1966) distribute eroding sediment into spit deposits and barrier islands (*e.g.,* Sandy Hook Spit). Throughout this area, average grain size on beaches decreases southward from the eroding coastal bluffs and as mineralogical composition of sand changes south of Long Beach Island (UPTEGROVE *et al.,* 1995; Figure 2).

Along the barrier island shoreline from Manasquan Inlet south to Cape May, islands range in length from 8 to 29 km, protecting estuarine and coastal plain environments from direct wave attack. Estuaries, salt marshes, and tidal channels encompass the Intracoastal Waterway landward of barrier islands (SMITH, 1996). Twelve inlets within the study area separate the barrier islands, resulting in complex tidal currents that produce lateral migration and redistribution of sand along adjacent shorelines (ASHLEY *et al.,* 1986; ASHLEY, 1987). To maintain navigability at these inlets, five have been stabilized with parallel rock jetties (Shark River, Manasquan, Barnegat, Absecon, and Cape May); three have been partially stabilized with one rock jetty or rock armoring on one shoreline (Great Egg, Townsends, and Hereford); and four have remained natural (Beach Haven, Little Egg, Brigantine, and Corson) (UPTEGROVE *et al.,* 1995). The five inlets with parallel rock jetties require regular maintenance dredging, and sand derived from these sites is placed on adjacent beaches as nourishment material in accordance with New Jersey's Rules on Coastal Zone Management (MAURIELLO, 1991).

METHODS

Existing literature and data were reviewed concerning offshore physical and benthic environments to evaluate potential changes resulting from sand mining. Regional geomorphic change, wave transformation, and circulation and sediment transport dynamics were analyzed, and two benthic characterization field surveys were conducted according to the following methods.

Physical Processes

Waves

The U.S. Army Corps of Engineers (USACE) Wave Information Study (WIS) results (1976 to 1995) for offshore New Jersey (WIS stations Au2067, Au2069, and Au2070) provided a detailed description of the regional wave climate for developing representative wave spectra. WIS stations are located at or near the offshore boundaries of wave transformation model grids (Figure 3). The closest available WIS station near the offshore boundary was used at each modeling reference grid. Rather than selecting average seasonal wave conditions, a detailed analysis was conducted to summarize existing WIS data into directional wave conditions and spectra. High-energy storm events were evaluated by reviewing existing literature on hurricanes and northeast storms (USACE, 1997) that passed through the New Jersey region. Analysis results, coupled with historical storm tracks and wave directions

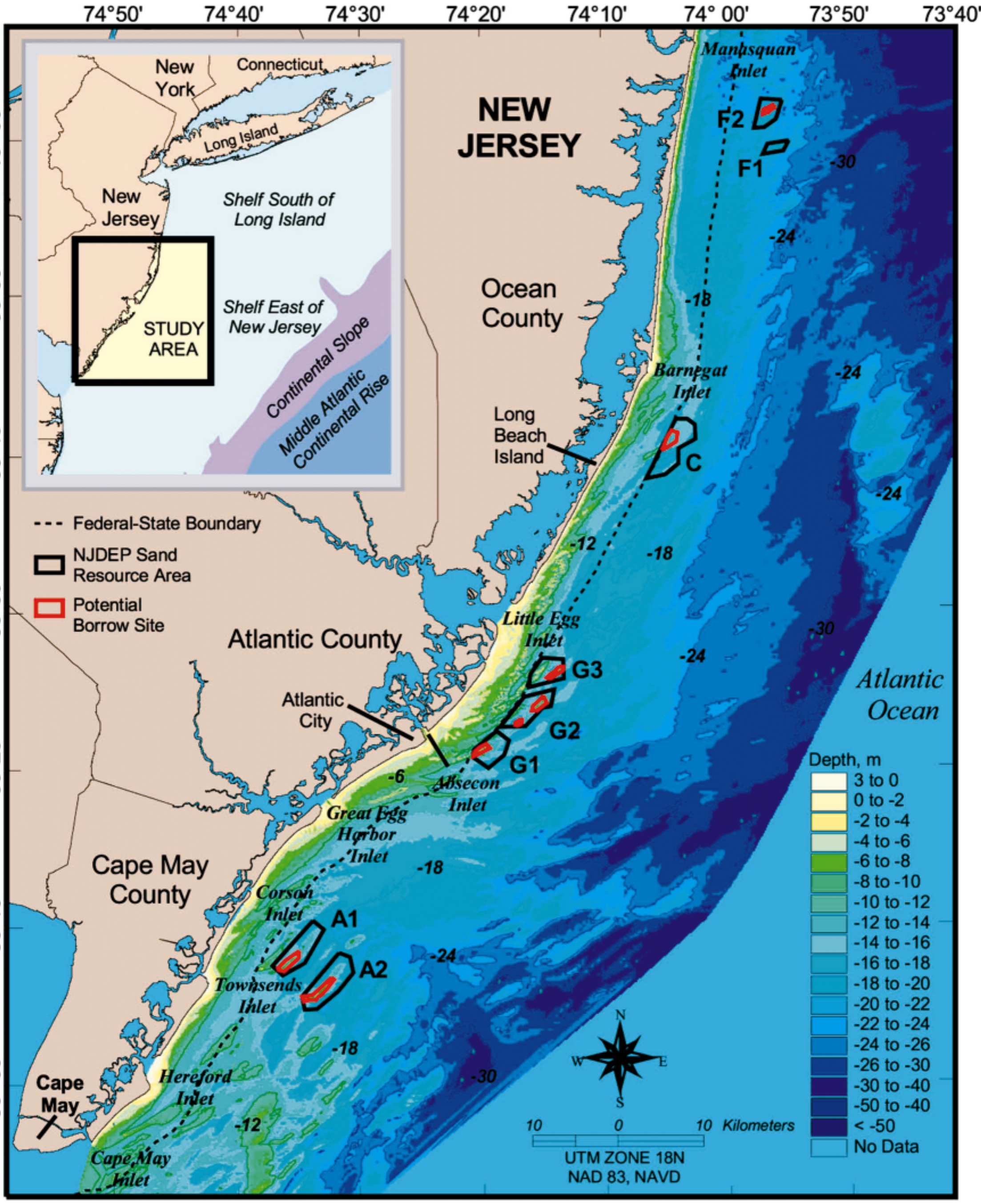

Figure 1. Location diagram illustrating sand resource areas and Federal-State boundary offshore New Jersey relative to 1934/77 bathymetry.

(1890 to 1997), were used to determine wave heights, directions, and frequencies for simulating 50-yr storm events. Surge values reported by KRAUS *et al.* (1988) for Monmouth Beach, New Jersey and GRAVENS *et al.* (1989) for Asbury Park to Manasquan, New Jersey documented storm surge levels associated with a 50-yr hurricane and northeaster. Storm surge heights of 2.71 m and 2.32 m were determined from the 50-yr hurricane and northeaster stage frequencies, respectively.

The spectral wave transformation model REF/DIF S (KIRBY and ÖZKAN, 1994) was used to evaluate changes in wave propagation across the New Jersey continental shelf relative to potential sand mining scenarios. Differences in wave heights between existing conditions and post-dredging sim-

Figure 2. Trends in average grain size along New Jersey beaches (modified after SMITH, 1996).

ulations were computed at each grid point within the model domain to document potential changes caused by specific sand mining scenarios. The model domain is divided into four reference grids (A, B1, B2, and C) due to the large region required for wave transformation modeling (Figure 3). Grids B1 and C are characterized by relatively smooth bathymetry and a uniform shoreline without inlets, whereas Grids A and B2 contain complex bathymetry and irregular coastlines with numerous inlets. Local bathymetry in these areas consists of many shoreface sand ridges, extending to depths of 10- to 15-m along a northeasterly trend. These features have a significant impact on incoming wave spectra.

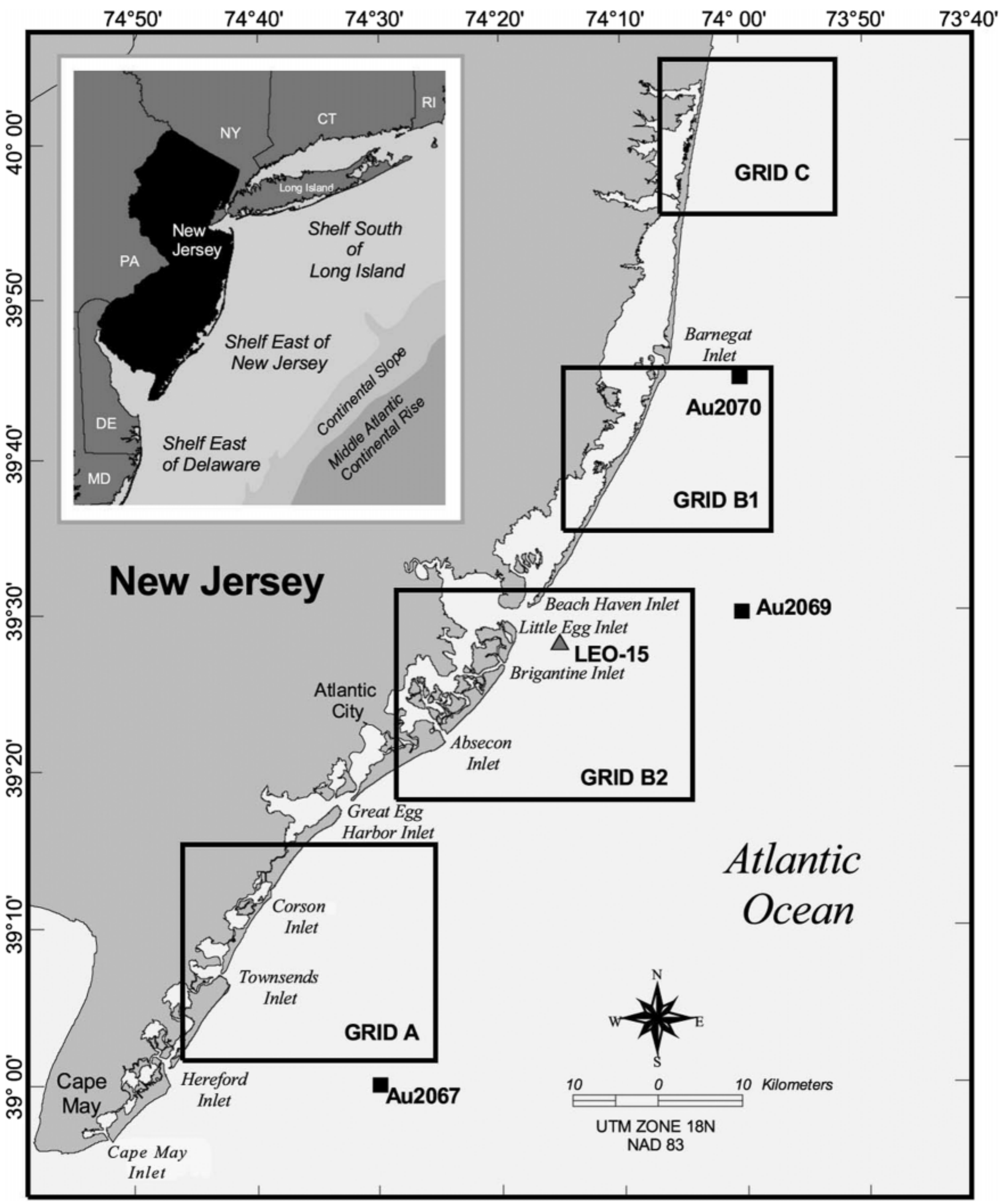

Figure 3. Locations of U.S. Army Corps of Engineers Wave Information Study (WIS) stations, current measurements, and wave modeling grids.

Proposed sand extraction volumes and sediment characteristics for borrow sites in Sand Resource Areas A1, A2, G1, G2, G3, C1, and F2 are listed in Table 1. Each borrow site was numerically excavated to simulate potential impacts of offshore dredging on physical processes. Existing condition wave simulations were subtracted from post-dredging wave results so that positive (negative) differences indicated an increase (decrease) in wave height related to sand mining at each borrow site.

Currents

Historical current records for data collected at LEO-15 (offshore Barnegat Inlet; Figure 3) were chosen for detailed analysis of current processes. The site is located in about 13-m water depth at 39°27.70′ N, 74°15.73′ W. Measurements were recorded by an S-4 current meter mounted approximately 1 m above the seafloor.

The LEO-15 measurements were obtained over an approx-

Table 1. *Sand resource characteristics at potential borrow sites in resource areas offshore New Jersey.*

Resource Area	Surface Area ($\times 10^6$ m^2)	Sand Volume ($\times 10^6$ m^3)	Excavation Depth (m)	D10 (mm)	D50 (mm)	D90 (mm)
A1	2.21	8.8	4	0.60	0.35	0.21
A2	2.60	7.8	3	1.60	0.62	0.30
G1	1.12	4.5	4	0.85	0.41	0.19
G2	1.44	4.3	3	1.40	0.66	0.30
G3	1.09	3.3	3	0.90	0.51	0.26
C1	2.04	6.1	3	0.40	0.20	0.14
F1	Too Small	Too Shallow	—	—	—	—
F2	0.69	2.1	3	2.40	0.46	0.27

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.

imate two-year period (August 1993 through August 1995); however, gaps in the two-year record due to instrument maintenance and data recovery made numerical analysis of the entire record difficult. Therefore, data were analyzed as a series of 30-to-90-day blocks, with statistics generated for each data block. Current data were first rotated from a north/east coordinate system to a cross-shelf/along-shelf coordinate system. Positive across-shelf flow is directed onshore and positive along-shelf flow is directed approximately northward.

Sediment Transport

Three independent sediment transport analyses were completed to evaluate physical environmental impacts of offshore sand mining. First, historical sediment erosion and accretion trends were quantified with sequential shoreline and bathymetric surveys to document long-term sediment movement (*e.g.,* Byrnes and Hiland, 1995; Byrnes and Baker, 2003). Historical map compilation and analysis procedures for surveys of coastal Alabama are documented in Byrnes *et al.* (2000). Second, annualized sediment infilling rates were estimated for each borrow site using analytical expressions developed by Madsen and Grant (1976) that incorporate information on wave orbital velocities, local current measurements, and sediment textural characteristics at borrow sites. Third, numerical techniques were developed to use nearshore wave information derived from REF/DIF S to evaluate changes in longshore sediment transport patterns (beach erosion and accretion) resulting from potential sand mining activities. This involved application of a wave-induced current model where the depth-averaged continuity equation and depth-averaged x and y momentum equations were integrated and time averaged (Winer, 1988; Ramsey, 1991).

Benthic Infaunal Characterization Surveys

Sampling Design

Benthic characterization field studies were conducted 3 to 8 May and 18 to 21 September 1998 within the eight sand resource areas and at three adjacent stations between sand resource area groups. Survey scheduling was designed to sample infaunal assemblages after the initial spring recruitment period, and then after summer recruitment.

A prescribed number of benthic grab samples was apportioned among surveys and resource areas. To determine the number of infaunal and sediment grain size samples to collect in May, surface area and percent of total surface area for each area were calculated. The percent of the total surface area for each of the resource areas then was multiplied by the total number of stations available for the project minus three for the adjacent stations, resulting in the number of samples per resource area. The next step was to determine the placement of infaunal and sediment grain size stations within each area to characterize existing assemblages. The goal in placement of the sediment grain size stations was to achieve broad spatial and depth coverage within the sand resource areas and, at the same time, ensure that the samples would be independent of one another to satisfy statistical assumptions. To accomplish this goal, a systematic sampling approach was used to provide broad spatial and depth coverage. This approach can, in many cases, yield more accurate estimates of the mean than simple random sampling (Gilbert, 1987). Grids were placed over figures of each resource area. The number of grid cells was determined by the number of samples per area. One sampling station then was randomly placed within each grid cell of each sand resource area. Randomizing within grid cells eliminates biases that could be introduced by unknown spatial periodicities in the sampling area. During May, 89 stations were sampled for sediment grain size using a Smith-McIntyre grab. Grabs at 30 of the 89 stations also were analyzed for infauna.

Placement of infaunal and sediment grain size stations for September was determined based on bathymetric post-plots and analyses of infaunal and sediment grain size samples collected during May. The design rationale for the September field effort was to sample May stations for temporal comparisons and further investigate areas of heterogeneity. For September, 60 stations were grab sampled for infauna and sediment grain size. Thirty of these 60 stations were in the same locations as the 30 Smith-McIntyre infaunal stations sampled during May. The remaining 30 Smith-McIntyre stations for September were located to broaden geographic coverage within the resource areas. Detailed maps of station locations for each resource area are provided in Byrnes *et al.* (2000).

A differential global positioning system was used to navigate the survey vessel to all sampling locations. Temperature, conductivity, dissolved oxygen, and depth were measured near bottom with a portable Hydrolab to determine if anomalous temperature, salinity, or dissolved oxygen conditions existed during field surveys.

Sediment Grain Size

A sub-sample (about 250 g) of sediment for grain size analyses was removed from each grab sample with a 5-cm diameter acrylic core tube, placed in a labeled plastic bag, and stored on ice. In the laboratory, grain size analyses were conducted using combined sieve and hydrometer methods according to recommended American Society for Testing Materials procedures. Samples were washed in demineralized water, dried, and weighed. Coarse and fine fractions (sand/silt) were separated by sieving through a U.S. Standard Sieve Mesh No. 230 (62.5 μm). Sediment texture of the coarse fraction was determined at 0.5-phi intervals by passing sediment through nested sieves. Weight of materials collected in each particle size class was recorded. Boyocouse hydrometer analyses were used to analyze the fine fraction (<62.5 μm). A computer algorithm determined size distribution and provided interpolated size information for the fine fraction at 0.25-phi intervals. Percentages of gravel, sand, and fines (silt + clay) were recorded for each sample.

Infauna

After removing the sediment grain size sub-sample, the remaining grab sample was sieved through a 0.5-mm sieve for infaunal analyses. Infaunal samples were preserved in 10% formalin with rose bengal stain. In the laboratory, organisms were identified to lowest practical identification level (LPIL) and counted.

Univariate summary statistics including number of taxa, number of individuals, density, Shannon's index of diversity (H') (PIELOU, 1966), Pielou's index of evenness (J') (PIELOU, 1966), and Margalef's index of species richness (D) (MARGALEF, 1958) were calculated for each sampling station. Station means of these summary statistics were then calculated for each resource area.

Spatial and temporal patterns for infaunal assemblages were examined using multivariate techniques, including cluster analysis, non-metric multidimensional scaling (MDS), and similarity percentage breakdown (SIMPER). These analyses were performed on a similarity matrix constructed from a raw data matrix consisting of taxa and samples (station-survey). The data matrix was constructed using taxa that contributed at least 2% of total infaunal abundance. This produced a data matrix of 67 taxa by 90 stations. To weight the contributions of common and rare taxa, raw counts of each taxon in a sample (n) were transformed to logarithms [$\log_{10}(n+1)$] prior to similarity analysis. Both normal (stations) and inverse (taxa) similarity matrices were generated using the Bray-Curtis index (BRAY and CURTIS, 1957). This matrix was clustered using the group averaging method that describes mean levels of similarity between groups of stations (FIELD *et al.,* 1982). Inverse similarity matrices were clustered using the flexible sorting method of clustering, performed with $\beta = -0.25$, a widely accepted value for this analysis (BOESCH, 1973). Cluster analysis was followed by MDS ordination of the similarity matrix to corroborate cluster results. Species accounting for observed assemblage differences among groups and within groups of stations were identified using the SIMPER procedure, which determines the average contribution of each species to characterizing a station group or discriminating between pairs of station groups (CLARKE, 1993). These analyses (MDS, SIMPER) were performed with the PRIMER v5 package (CLARKE and GORELY, 2001).

The extent to which station groups formed by normal cluster analysis of infaunal data could be explained by environmental variables was examined by canonical discriminant analysis (CDA) (SAS INSTITUTE, INC. STAFF, 1989), which identifies the degree of separation among pre-defined groups of variables in multivariate space. Environmental variables used for the CDA were survey (categorical), water depth, percent gravel, percent sand, and percent fines.

RESULTS

Physical Processes

Wave Transformation Modeling

Potential dredging impacts at offshore borrow sites were determined by wave modeling to estimate refraction, diffraction, shoaling, and wave breaking. Wave refraction and diffraction generally result in an uneven distribution of wave energy that determines the magnitude and direction of sediment transport along a coast. For the outer coast of New Jersey, wave spectra indicated that the dominant direction of wave propagation was from north-to-south. Wave modeling results also supplied input for nearshore circulation and sediment transport models.

Existing Conditions. Wave transformation simulations identified specific areas of wave convergence, divergence, and shadow zones. Non-storm significant wave heights and angles experienced little variation seaward of the 20-m depth contour, where the wave field began to be influenced by bathymetry. Significant bathymetric features (*e.g.,* shore-attached, northeast extending linear ridges and swales, offshore shoals, bathymetric depression, *etc.*) within each modeling grid were the primary cause of increases and decreases in wave height and angle. Influence of these bathymetric features on the wave field along the coast changed as waves approached from various directions.

The region offshore Townsends and Corson Inlets (Areas A1 and A2; Figure 1) had a relatively consistent longshore wave height distribution. Several areas of wave convergence and divergence (0.2 to 0.3 m) were caused by shoals surrounding Areas A1 and A2. These shoals focused wave energy at various locations along the coast depending on wave approach direction. Offshore Little Egg Inlet (Areas G1, G2, and G3), wave transformation again was influenced by numerous linear ridges. Areas of wave height convergence and divergence (0.3 m) and changing wave direction appear most frequently near Brigantine Inlet. The area south of Barnegat Inlet (Area C1) experienced minor changes in wave height distribution along the coast and mild shoreline retreat. Shoals and swales south of Area C1, as well as offshore linear ridges to the north, produced wave height changes ranging from 0.1 to 0.3 m within the modeling grid. Wave energy focused by offshore ridges most often influenced beach changes along the northern 5 km of Long Beach Island.

The region seaward of northern Barnegat Bay (Area F2) also experienced wave height changes (0.2 to 0.3 m) produced by offshore shoals and swales. Consistent wave focusing was observed for the shoal within Area F2, as well as shoals to the south and southeast of F2. Wave energy focused by these features may impact regions seaward of northern Barnegat Bay depending on approach direction.

Storm wave propagation patterns were similar to those documented for directional approach trends. As with all storm wave simulations, wave convergence and divergence patterns were less pronounced because changes caused by bathymetric features were small when compared with large input wave heights. An increase in wave height relative to adjacent areas was documented where wave convergence occurred (BYRNES *et al.,* 2000). For example, the shoal in Area F2 produced wave convergence resulting in 6.0 m wave heights during a typical 50-yr northeast storm. In most cases, storm wave heights exceed 3.0 to 4.0 m along the coast.

Existing Versus Post-Dredging Conditions. Differences in wave heights between existing and post-dredging conditions offshore southern New Jersey (Areas A1 and A2) indicated maximum wave height increases of 0.3 m for wave approaching from the east-southeast (about 20% increase relative to existing conditions) at the borrow sites. By the time waves reach the coast, wave height increases at the borrow site dissipated to an average of about 0.1 m (8%) relative to existing conditions. For most directional cases, wave height modifications caused by sand mining dissipated before reaching the coast (*e.g.,* Figure 4). The magnitude of modifications increased as the magnitude of waves increased or when the orientation of borrow sites aligned with waves to produce maximum impact.

For sand borrow sites in Areas G1, G2, and G3 (Grid B2), maximum wave height changes ranged from 0.16 to 0.6 m. Similar to Areas A1 and A2, most modifications caused by sand mining dissipate relatively quickly as waves advance toward the coast and break (Figure 5). Wave height increases relative to existing conditions at the coast ranged from 0.25 m (16%) south of Brigantine Inlet for a southeast wave approach to 0.05 m (4%) south of Little Egg Inlet for waves from the south-southeast. The average increase in wave height for all wave approach directions that resulted from simulated offshore sand mining in Grid B2 was 0.13 m (10%).

For borrow sites in Areas C1 and F2 (northernmost borrow sites; Grids B1 and C), maximum changes in wave height ranged from 0.06 to 0.2 m, smaller than that estimated for offshore southern New Jersey. However, changes in wave height caused by sand mining do not dissipate much before reaching the coast (Figure 6). A steeper shoreface profile offshore northern beaches allowed more wave energy to reach the coast than gently sloping nearshore areas to the south. Maximum increases in wave height at the coast resulting from simulated sand mining in Area C1 was 0.12 m (8%) for southeast wave approach. For all wave approach simulations in Grid B1, average wave height increase was 0.09 m (5%). For the northernmost borrow site in Grid C, maximum wave height increase at the coast was 0.15 m (9%) for waves from the northeast. Average wave height increase for all approach directions in Grid C was 0.09 m (5%).

During extreme wave conditions (*e.g.,* a 50-yr storm), wave heights increased from 0.4 to 1.4 m adjacent to offshore borrow sites, suggesting a rather significant change. However, this represented a change of less than 20% relative to existing conditions. Due to shoreline and borrow site orientations, hurricane waves produced greater changes at Areas A1, A2, G1, G2, and G3, and northeast storm waves had greater influence on Areas C1 and F2. Most wave energy increases resulting from simulated dredging at offshore borrow sites were dissipated before waves reached the coast, especially along southern New Jersey beaches. As such, wave height increases were less than 0.4 m (10%) along most of the coast.

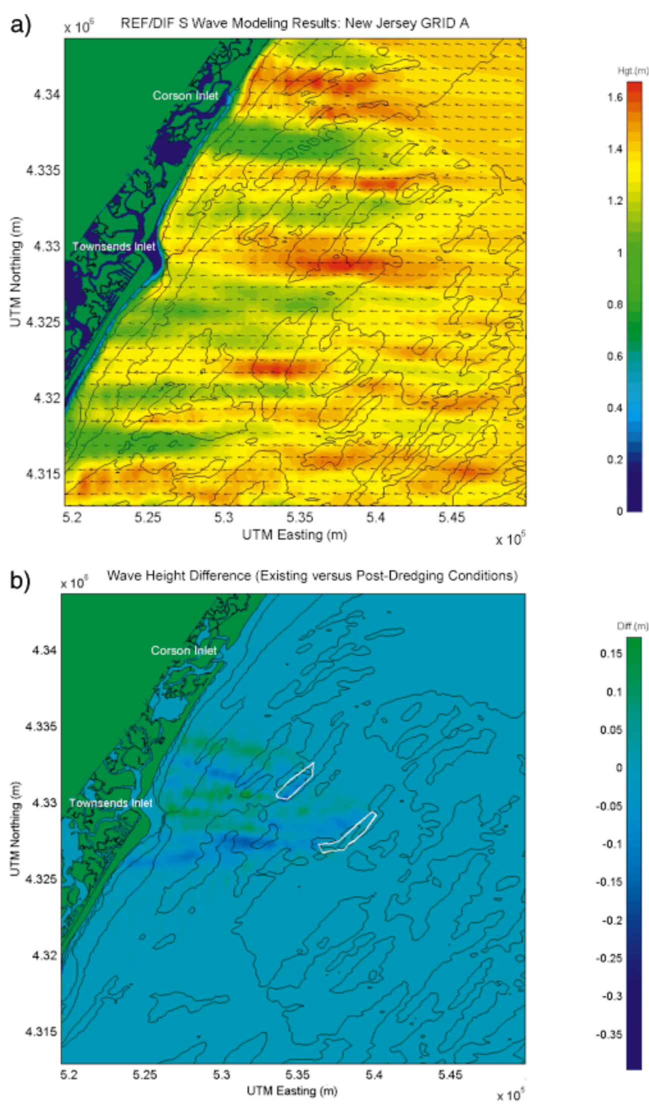

Figure 4. Spectral wave modeling results for Grid A. a) Existing conditions for an eastern approach direction. b) Wave height modifications resulting from offshore mining at Sand Resource Areas A1 and A2 for the eastern approach simulation (most common approach direction for non-storm waves). Green shades identify areas of increased wave height, and blue shades identify areas of decreased wave height.

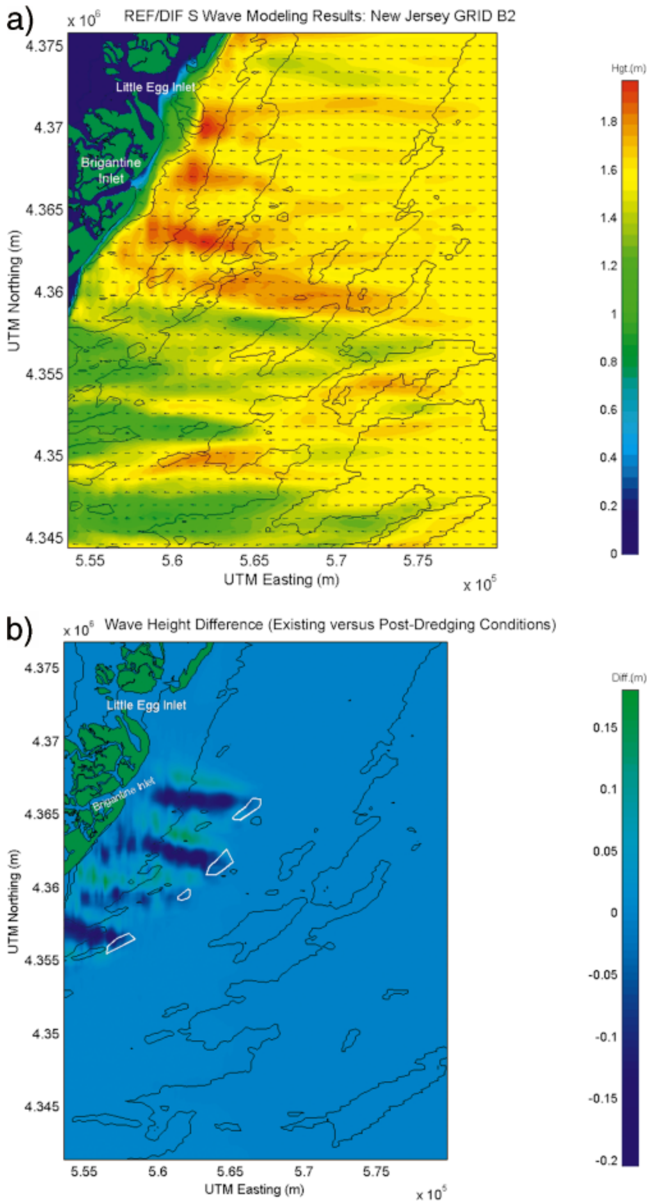

Figure 5. Spectral wave modeling results for Grid B2. a) Existing conditions for an eastern approach direction (0 degree bin). b) Wave height modifications resulting from offshore mining at Sand Resource Areas G1, G2, and G3 for the eastern approach simulation.

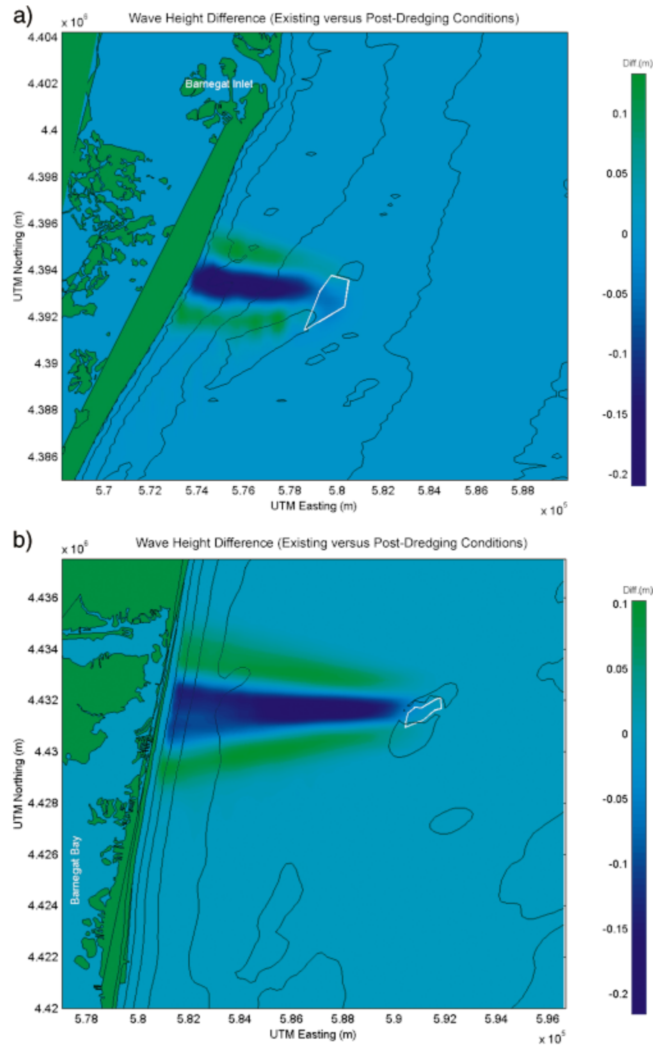

Figure 6. Wave height modifications resulting from simulated offshore sand mining at Grid B1 (a) and Grid C (b) for an eastern wave approach.

Currents

Bottom current data for offshore New Jersey (seaward of Little Egg Inlet) revealed considerable variability in flow speed and direction. Mean flow was to the southwest along inner shelf bathymetric contours. Strongest flow was observed in the along-shelf direction, with peak velocities of nearly 50 cm/sec (1 knot) to the south; maximum northward currents reached 37 cm/sec. Frequent flow reversals were noted.

Along-shelf currents were dominated by wind-driven processes, accounting for about 70% of total current energy. Wind-driven processes were greatest in winter; however, wind-driven flows appeared strongly biased by singular events, such as local responses to storm winds or non-locally generated free waves that influenced the magnitude of wind-driven current energy (NOBLE *et al.,* 1983). This suggests that singular events, with corresponding higher currents, have greatest potential to transport sand. If so, regional sediment transport patterns are predominately in the along-shelf direction, with a net transport oriented in the direction of mean southerly flow.

In the cross-shelf direction, mean flow was oriented onshore, consistent with upwelling processes that push bottom waters onto the shelf. Maximum cross-shelf flow was 31 cm/sec (directed onshore); minimum flow was 13 cm/sec (directed offshore). Cross-shelf bottom currents were influenced most significantly by semi-diurnal tides, with a mean onshore flow. Wind-driven currents were found to be less significant in the cross-shelf direction. Seasonal variability was most significant for wind-driven currents. Winter and autumn data records were most energetic, with summer and spring data sets having smaller energy values.

Sediment Transport

Wave transformation modeling and current measurements provided baseline coastal processes information for the study area. However, the most important data sets for documenting physical processes impacts from offshore sand mining were quantified changes in sediment transport dynamics.

Historical Trends. Regional geomorphic changes for the period 1843/91 to 1934/77 were analyzed to assess long-term, net coastal sediment dynamics using shoreline and bathymetric surveys (composite bathymetric surfaces included data sets for the periods 1843 to 1891 and 1934 to 1977; see BYRNES *et al.,* 2000). Shoreline position and nearshore bathymetric change documented four important sediment transport trends. First, the predominant direction of transport throughout the New Jersey coastal zone was north to south. Southern Long Beach Island (north of Little Egg Inlet) and southern Island Beach (north of Barnegat Inlet) have migrated at a rate of about 14 m/yr to the south since 1839/42. Ebb-tidal shoals at all inlets in the study area are oriented to the south, and channels are aligned northwest-southeast.

Second, the most dynamic geomorphic features within the study area are ebb-tidal shoals associated with inlets along the southern barrier island chain. Areas of significant erosion and accretion were documented for the period 1843/91 to 1934/77, reflecting wave and current dynamics at entrances, the influence of engineering structures on morphologic change, and the contribution of littoral sand transport from the north to sediment bypassing and shoal migration (Figure 7).

Third, alternating bands of erosion and accretion on the continental shelf east of the Federal-State boundary illustrated relatively slow but steady reworking of the upper shelf surface as sand ridges migrate from north to south. The process by which this was occurring at Areas G1, G2, and G3 suggested that a borrow site in this region would fill with shelf sediment transported from an adjacent site at a rate of about 62,000 to 125,000 m^3/yr. At Areas A1 and A2, the potential transport rate increased to 160,000 to 200,000 m^3/yr.

Finally, net alongshore changes in erosion and accretion, determined from seafloor changes in the littoral zone between Little Egg Inlet and the beach south of Hereford Inlet, indicated an increasing transport rate to the south from about 70,000 m^3/yr south of Little Egg Inlet to 190,000 to 230,000 m^3/yr at Townsends and Hereford Inlets. Variations in longshore transport are evident in patterns of change recorded on Figure 7 (alternating zones of erosion and deposition along the shoreline). Areas of largest net transport exist just south of entrances as a result of natural sediment bypassing from updrift to downdrift barrier beaches. These net transport rate estimates compare well with numerical model simulations of longshore transport rates and provide a measured level of confidence in wave and sediment transport modeling capabilities relative to impacts associated with sand dredging from selected borrow sites.

Borrow Site Infilling. Predicted sediment infilling rates at borrow sites ranged from a minimum of 28 m^3/day (about 10,000 m^3/yr; Area F2) to a high of 450 m^3/day (164,000 m^3/yr; Area A1); infilling times varied from 54 (Area A1) to 303 years (Area C1). Sediment that replaces sand mined from a borrow site will fluctuate based on location, time of dredging, and storm characteristics following dredging episodes. However, infilling rates and sediment types are expected to reflect natural variations that currently exist within sand resource areas. The range of infilling times was based on the volume of sand numerically dredged from a borrow site, as well as the estimated sediment transport rate. Predicted sediment infilling rates were slightly lower than net transport estimates derived from historical data sets, but the two estimates are within the same order of magnitude (10,000 to 160,000 m^3/yr versus 62,000 to 200,000 m^3/yr, respectively). Simulated infilling rates would be larger if the impact of storm events were incorporated in the analysis.

Nearshore Sediment Transport Modeling. Sand mining impacts on net littoral transport east of Areas A1 and A2 illustrated a defined but minor change. Due to the relatively shallow and wide continental shelf along the southern portion of the New Jersey coast, the percent difference in net longshore sand transport associated with offshore mining was small (approximately 7% of the existing value) relative to resource areas to the north.

Wave shadow zones are indicated by a reduction in south-directed wave energy. Shadow zones landward of Areas A1 and A2 are located approximately 5 km and 1 km north of Townsends Inlet, respectively (Figure 8a). The largest increase in net annual south-directed transport occurs between shadow zones (3 km north of Townsends Inlet), where borrow sites in Areas A1 and A2 have wave energy refracted to the south and north, respectively. An increase in wave energy at the shoreline is responsible for increased south-directed transport between shadow zones.

Because the distance from shore to Areas G2 and G3 is relatively small (approximately 5 km), the potential shoreline impact region is more confined than for Area A2. For borrow sites in Areas G2 and G3, the maximum variation in net annual longshore sand transport was approximately 9% of the existing value (Figure 8b). Only a single shadow zone landward of Areas G2 and G3 existed approximately 1 km south of Brigantine Inlet. This shadow zone was associated with a significant reduction in south-directed wave energy. The largest increase in net annual longshore transport occurred south of the shadow zone (approximately 2 km south of Brigantine Inlet). However, it is unclear whether the shadow zone or the region of increased south-directed wave energy was a result of dredging in Areas G2 (one borrow site), G3 (two borrow sites), or a combination of the three borrow sites.

For Area C1, southeast and east wave conditions dominated the wave record. However, a series of shadow zones landward of Area C1 occurred as a result of wave refraction generated by all modeled wave conditions. The largest shadow zone was generated by waves propagating from the east. In addition, waves propagating from the east-southeast caused

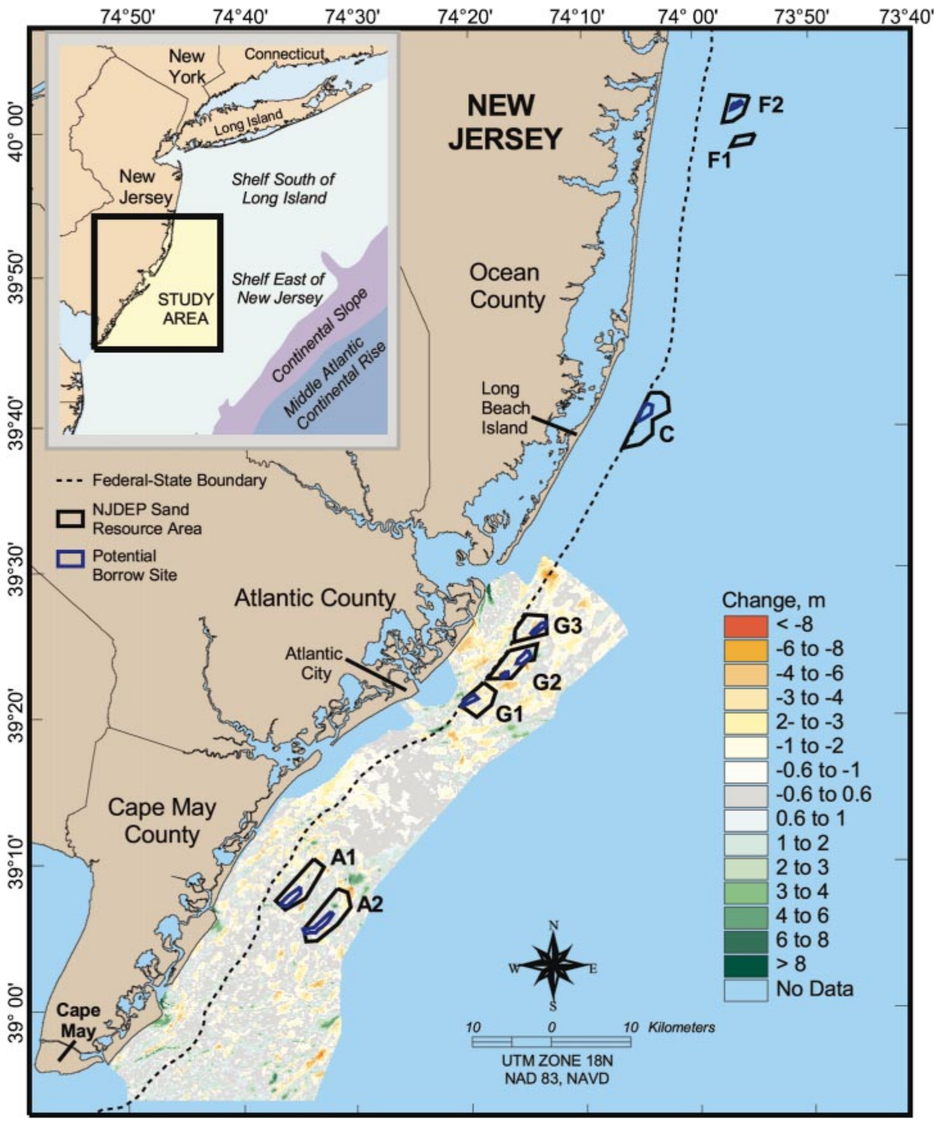

Figure 7. Nearshore bathymetric change (1843/91 to 1934/77) for the southeastern New Jersey continental shelf.

a reduction in south-directed transport. The maximum variation in net annual longshore sediment transport was about 20% of the existing annual transport rate.

For the borrow site in Area F2, maximum variation in net annual longshore sand transport was approximately 17% of existing conditions. Similar to Area C1, a relatively low net longshore sand transport rate resulted in a high percentage impact to the annual transport rate; however, the maximum change of approximately 12,700 m^3/yr was similar to modeled change for Areas A1, A2, C1, G1, G2, and G3. A shadow zone landward of Area F2 is located approximately 6 km south of Manasquan Inlet. Likewise, the largest increase in north-directed transport occurred on either side of the shadow zone (approximately 4 and 8 km south of Manasquan Inlet, respectively; see BYRNES *et al.,* 2000).

For average annual conditions, net longshore sand transport rates were approximately equal landward of borrow sites along the New Jersey coast. The absolute value of the mean difference between existing and post-dredging conditions was relatively consistent, ranging between 9,000 (20%) and 14,900 m^3/yr (7%).

Benthic Environment

Water Column

During May, bottom temperatures ranged from 8.2°C at Area F2 to 11.2°C in Area A1, salinity values ranged from 28.5 ppt in Area C1 to 33.8 ppt at Area F2, and dissolved oxygen measurements ranged from 6.41 mg/L in Area G2 to 9.60 mg/L at Area F2. During September, bottom tempera-

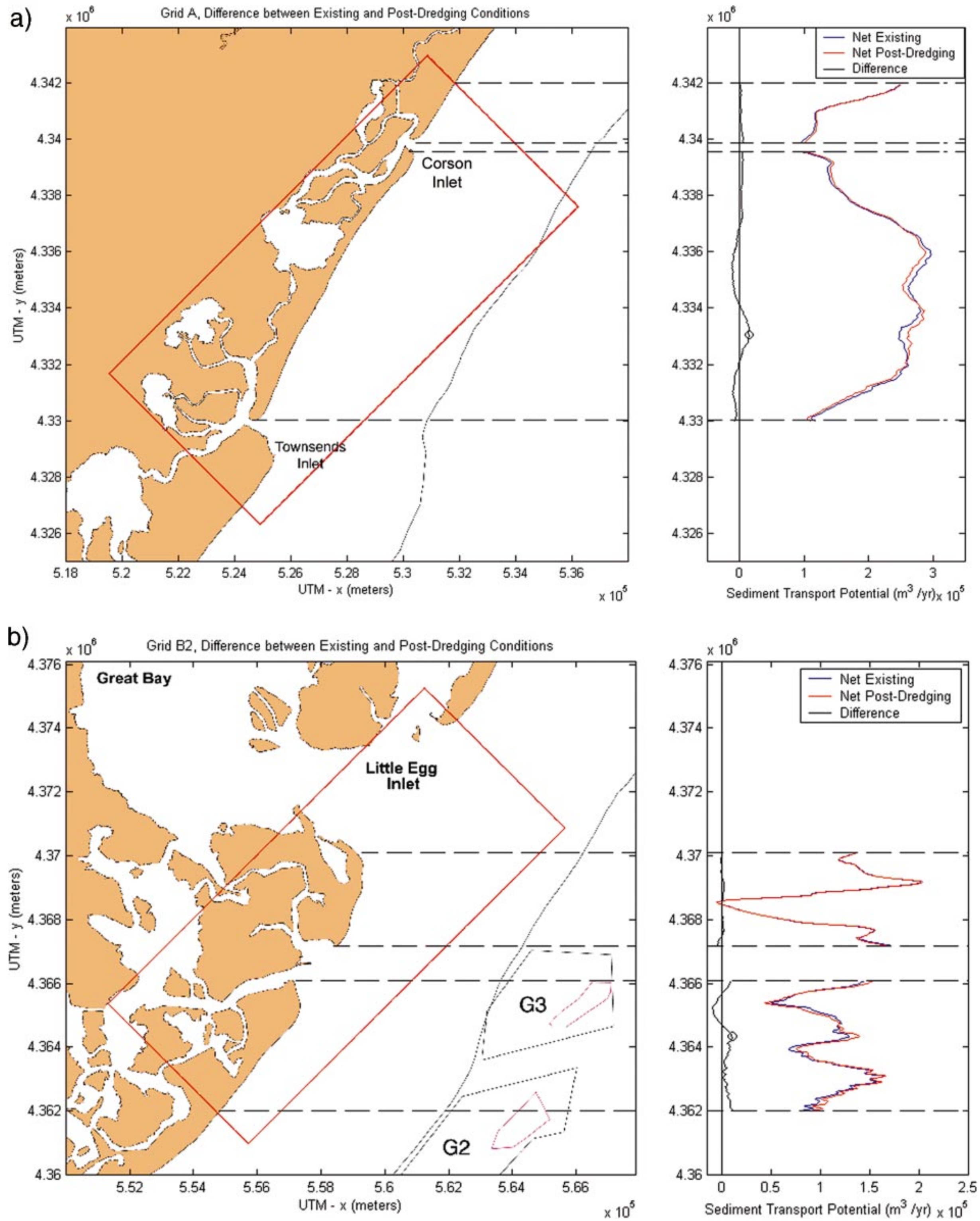

Figure 8. Difference in average annual transport rates associated with simulated dredging at sand borrow sites in a) Grid A and b) Grid B2.

Table 2. *Mean percentage (standard deviation) of sediment types in grab samples collected in the sand resource areas during May and September 1998.*

Resource Area (n)	Mean % Gravel (SD)	Mean % Sand (SD)	Mean % Fines (SD)
A1 (22)	10.78 (20.11)	88.62 (20.01)	0.19 (0.76)
A2 (26)	12.74 (14.71)	85.57 (15.70)	0.03 (0.10)
C1 (27)	19.97 (28.21)	78.09 (28.09)	1.42 (7.25)
F1 (7)	15.95 (12.48)	83.68 (12.46)	0.00 (0.00)
F2 (11)	22.45 (22.59)	77.15 (22.52)	0.00 (0.00)
G1 (14)	6.62 (12.71)	90.71 (16.24)	1.44 (4.76)
G2 (20)	0.55 (0.86)	93.47 (18.17)	4.20 (17.86)
G3 (16)	1.36 (3.61)	97.87 (3.58)	0.00 (0.00)

tures ranged from 12.5°C for Area F2 to 22.2°C in Area G1, bottom salinity values ranged from 27.6 ppt in Areas G1 and G2 to 33.4 in Area A2, and bottom dissolved oxygen values ranged from 2.94 mg/L in Area G3 to 6.48 mg/L in Area G2. Hypoxic and anoxic conditions were not found during May or September.

Sediment Grain Size

Proportions of gravel, sand, and fines (silt + clay) varied within and among resource areas (Table 2). Areas A1 and A2 included sand stations and a few gravel stations. C1 stations generally had varied amounts of gravel and a few sand stations. F1 and F2 samples contained varied amounts of gravel. Samples from G1, G2, and G3 were mostly sand with only minor amounts of gravel at a few stations. There were little or no fines in the sediment samples.

Infauna

The archiannelid *Polygordius* (LPIL) was numerically dominant in the grabs, comprising 18% of all infauna collected. Other than *Polygordius* (LPIL), taxa that were among the top 10 numerical dominants during both surveys included nut clam (*Nucula proxima*) and non-identified oligochaetous annelids and rhynchocoels. Mean taxa evenness (J') varied little between surveys but was variable between resource areas (Table 3). J' ranged from 0.51 (Area F1) to 0.73 (Area A2) in May and 0.60 (Area F1) to 0.71 (Area G2) in September. Mean taxa diversity (H') and richness (D) were higher in September compared to May for all resource areas except Area F2 diversity. Mean values of H' ranged from 1.64 (G1) to 2.37 (A1) in May and from 2.08 (F2) to 2.48 (G2) in September. Mean values of D ranged from 3.71 (G1) to 5.67 (A1) in May and from 4.30 (F2) to 6.68 (G1) in September.

Cluster analysis and MDS ordination identified seven station (sample) groups (Groups A through G) that were similar with respect to species composition and relative abundance (Figure 9). Ten of the 90 stations did not cluster with other stations, were generally depauperate, and were assigned to outlier groups (X and Y). Dispersion patterns were strong only for some of the clustered stations (Figure 9a), and no patterns emerged with respect to survey (Figure 9b). Lack of well-defined patterns in the MDS ordination was reflected by the high (0.22) stress value. Table 4 presents the distribution of stations by survey and resource area. Group D included stations sampled exclusively in May, whereas Groups B, E, and G included only September samples. Three groups (A, C, and F) included samples collected during both surveys. Groups B (21 stations) and F (31 stations) together contained most of the project samples (Table 4). Except for F1 and F2, resource areas were represented by multiple station groups. Groups with consistent sediment size across clustered stations were Groups B and D (sand) and Groups A and E (gravel) (Table 5). Samples in Groups C and F had variable sediment regimes.

Taxa typifying station groups, determined with SIMPER, are presented in Table 6. *Polygordius* (LPIL) contributed to station similarities in six of the seven station groups, an indication of the ubiquity of this taxon during the surveys. Station Groups C and F had lower average levels of similarity

Table 3. *Summary of infaunal community statistics by survey and resource area.*

Area (n)	Mean No. Taxa (SD)	Mean No. of Individuals (SD)	Mean Density (individuals/m²) (SD)	Mean Diversity (H') (SD)	Mean Evenness (J') (SD)	Mean Richness (D) (SD)
			May			
A1 (4)	37 (20)	898 (846)	8,975 (8,463)	2.37 (0.61)	0.67 (0.16)	5.67 (2.28)
A2 (4)	21 (7)	217 (181)	2,173 (1,814)	2.20 (0.69)	0.73 (0.20)	3.85 (1.01)
C1 (5)	28 (9)	625 (616)	6,254 (6,158)	2.01 (0.52)	0.63 (0.20)	4.49 (0.72)
F1 (2)	31 (1)	609 (441)	6,090 (4,412)	1.74 (0.46)	0.51 (0.14)	4.75 (0.49)
F2 (2)	26 (13)	351 (343)	3,505 (3,429)	2.25 (0.24)	0.72 (0.05)	4.26 (1.50)
G1 (3)	21 (5)	565 (612)	5,647 (6,124)	1.64 (1.10)	0.54 (0.37)	3.71 (0.90)
G2 (4)	27 (8)	757 (866)	7,570 (8,658)	1.91 (0.76)	0.59 (0.26)	4.26 (0.77)
G3 (3)	33 (18)	878 (1,296)	8,783 (12,960)	2.10 (0.80)	0.64 (0.30)	5.35 (1.41)
			September			
A1 (9)	41 (11)	734 (625)	7,339 (6,245)	2.41 (0.37)	0.66 (0.11)	6.24 (1.26)
A2 (8)	33 (8)	447 (366)	4,468 (3,660)	2.40 (0.31)	0.69 (0.08)	5.53 (1.19)
C1 (11)	28 (6)	384 (447)	3,842 (4,473)	2.15 (0.76)	0.65 (0.23)	5.10 (1.15)
F1 (3)	36 (4)	507 (393)	5,073 (3,933)	2.14 (0.39)	0.60 (0.13)	5.85 (0.12)
F2 (5)	26 (5)	339 (109)	3,392 (1,092)	2.08 (0.34)	0.64 (0.11)	4.30 (0.83)
G1 (6)	43 (10)	644 (351)	6,438 (3,512)	2.33 (0.51)	0.62 (0.13)	6.68 (1.52)
G2 (8)	35 (7)	800 (1,207)	8,000 (12,067)	2.48 (0.41)	0.71 (0.12)	5.70 (1.14)
G3 (7)	40 (7)	547 (392)	5,470 (3,920)	2.42 (0.52)	0.66 (0.16)	6.44 (0.93)

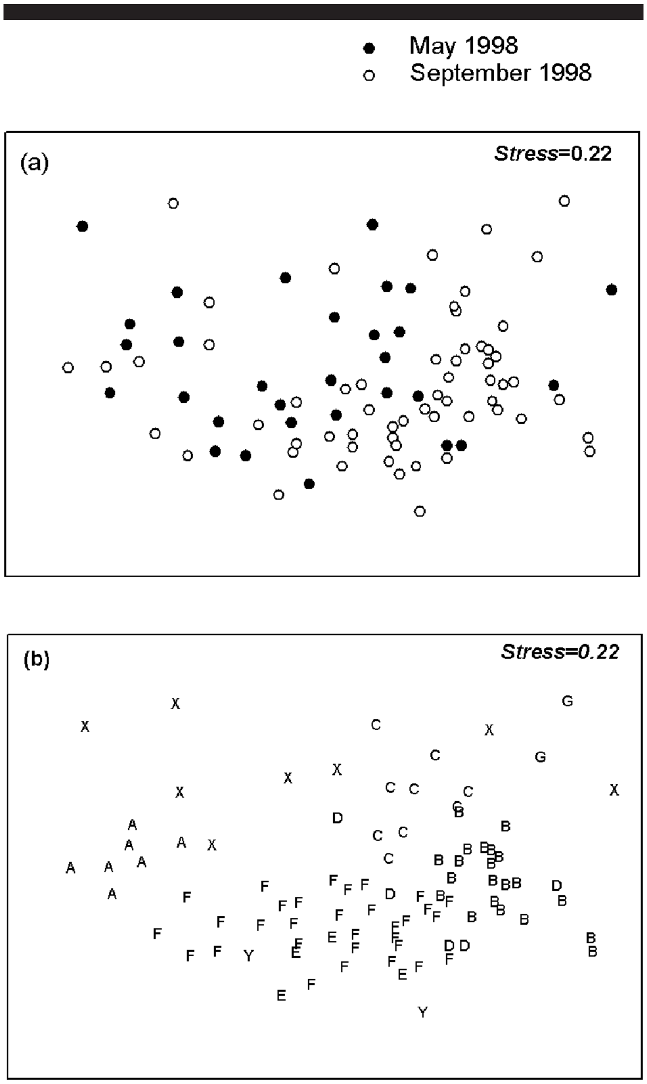

Figure 9. Multidimensional scaling plots of infaunal samples collected during May and September 1998 at eight offshore New Jersey sand resource areas labeled by (a) survey and (b) station groups determined from cluster analysis.

than other groups, indicating more assemblage variability between stations. Inverse cluster analysis resulted in five groups of taxa (Groups 1 through 5) that reflected their co-occurrence in sand resource area samples (Table 7).

Station groups defined by normal cluster analysis were analyzed using canonical discriminant analysis (CDA) to determine which environmental factors correlated best with the variability in infaunal assemblages. The first CDA axis correlated best with percent gravel (0.6978) and percent sand (−0.6814). The second CDA axis correlated best with latitude (Northing [0.8371]) and longitude (Easting [0.7659]). Mean scores of canonical variables were plotted on the first two CDA axes for Station Groups A through G (Figure 10). The first two CDA axes accounted for 77% of the variance explained by the environmental factors.

Table 4. *Distribution by survey and resource area for station groups resolved from multidimensional scaling ordination and normal cluster analysis.*

Station	Resource Area										
Group	A1	A2	C1	F1	F2	G1	G2	G3	Adj. 1	Adj. 2	Adj. 3
					May						
A	1		2							1	
B											
C	1						2	2	1		
D	1	1	1				1	1			
E											
F	1	1	1	2	2	1	1				1
G											
X/Y		2	1			2					
					September						
A			2							1	
B	6	3				5	4	3			
C	1					1			1		
D											
E		3					1				
F		1	6	3	5		2	3			1
G							1	1			
X/Y	2		3								

DISCUSSION

Physical Processes

Extraction of sediment from offshore borrow sites may result in modifications to physical processes at and adjacent to borrow sites and in the nearshore zone of New Jersey. Incident wave heights and angles experienced little variation seaward of the 20-m depth contour. However, landward of this depth to the shoreline, wave field changes were controlled by bathymetric variations. The region offshore Townsends and Corson Inlets (Grid A) illustrated several regions of wave convergence and divergence caused by shoals surrounding Areas A1 and A2. These features focused wave energy at various locations along the coast depending on wave approach direction. Seaward of Little Egg and Brigantine Inlets (Grid B2), wave transformation patterns again were controlled by numerous offshore sand ridges and swales. Increased wave heights appeared most frequently near Brigantine Inlet. The region south of Barnegat Inlet experienced a relatively consistent wave height distribution along the shoreline. However, wave energy focused by shoals and swales south of Area C1 most often impacted beaches along

Table 5. *Mean percentage (standard deviation) by sediment type for station groups resolved from multidimensional scaling ordination and normal cluster analysis.*

Station Group (n)	Mean % Gravel (SD)	Mean % Sand (SD)	Mean % Fines (SD)
A (7)	47.75 (30.48)	51.30 (29.73)	0.50 (1.23)
B (21)	0.69 (3.02)	98.63 (2.98)	0.00
C (9)	8.99 (16.46)	81.35 (27.60)	5.78 (25.99)
D (5)	2.77 (4.20)	96.82 (4.29)	0.00
E (4)	8.33 (3.85)	84.54 (15.08)	0.00
F (31)	12.13 (16.61)	87.22 (16.49)	0.04 (0.22)
G (2)	0.00 (0.00)	86.38 (12.41)	0.00

Table 6. *Average abundance of infaunal species accounting for at least 50% of the within group similarity in station (sample) groups A through G. Numbers in bold represent the average similarity for each group as a whole.*

Group	Taxa	Average Abundance	Average Similarity
A	*Hemipodus roseus*	55.57	11.15
	Pseudunciola obliquua	354.43	9.63
	Polygordius (LPIL)	32.00	9.02
			50.47
B	*Tanaissus psammophilus*	26.81	5.70
	Polygordius (LPIL)	150.24	5.43
	Acanthohaustorius millsi	23.52	5.19
	Astarte castanea	20.05	4.59
	Spiophanes bombyx	10.19	2.80
	Caulleriella sp. J	34.19	2.01
			49.98
C	*Tanaissus psammophilus*	415.33	6.21
	Polygordius (LPIL)	33.56	5.30
	Mytilus edulis	30.33	5.01
	Tellina agilis	104.56	4.28
	Chiridotea tuftsi	10.44	3.48
	Tanaissus psammophilus	415.33	6.21
			45.99
D	*Pisione remota*	14.40	13.82
	Acanthohaustorius millsi	11.60	12.95
	Polygordius (LPIL)	8.80	11.52
			56.36
E	*Polygordius* (LPIL)	27.75	8.11
	Spiophanes bombyx	61.25	8.09
	Aricidea catherinae	11.00	6.67
	Brania wellfleetensis	19.25	6.39
			54.23
F	*Polygordius* (LPIL)	171.32	12.15
	Spiophanes bombyx	59.74	9.24
	Caulleriella sp. J	26.68	3.74
			45.21
G	*Spisula solidissima*	799.00	14.82
	Unciola irrorata	51.00	9.13
	Dispio uncinata	29.00	7.64
	Ampelisca sp. X	20.00	6.02
			65.37

the northern end of Long Beach Island. The area seaward of northern Barnegat Bay also experienced wave height changes produced by offshore shoals and swales. Wave focusing by the shoal within Area F2 was common for all wave conditions. Similar wave propagation patterns at all sand resource areas were observed for the 50-yr hurricane and northeast storm.

Post-dredging model simulations were performed by numerically excavating selected borrow sites for each of the four modeling grids. Differences in wave height between existing and post-dredging conditions indicated maximum wave height increases for directional approach simulations of 0.3 m (about 17% of the initial wave height). The magnitude of modifications increased as the magnitude of waves increased, or when borrow site orientation was aligned with waves to produce maximum impact (*e.g.,* southeast approach at Areas A1 and A2). South of Brigantine Inlet, maximum wave height changes dissipated quickly as waves advanced toward the coast and broke. Landward of Areas C1 and F2, maximum changes did not dissipate as rapidly due to the relatively

Table 7. *Infaunal species groups resolved from inverse cluster analysis of all samples collected in the sand resource areas.*

GROUP 1

Polygordius (LPIL)
Tanaissus psammophilus
Pseudunciola obliquua
Spiophanes bombyx
Spisula solidissima
Tellina agilis
Caulleriella sp. J
Protohaustorius wigleyi
Rhepoxynius hudsoni
Acanthohaustorius millsi

GROUP 2

Pisione remota
Astarte castanea
Hemipodus roseus
Mytilus edulis
Crenella decussata
Lumbrinerides acuta
Aricidea cerrutii
Hesionura elongata
Protodorvillea kefersteini
Parougia caeca
Spio setosa

GROUP 3

Petricola pholadiformis
Nereis succinea
Anachis lafresnayi
Brania wellfleetensis
Cirriformia grandis
Chiridotea tuftsi
Sigalion arenicola
Politolana polita
Donax variabilis
Bathyporeia parkeri
Oxyurostylis smithi
Tectonatica pusilla
Echinarachnius parma
Exogone hebes
Parapionosyllis longicirrata
Streptosyllis arenae
Capitella capitata
Diastylis polita
Ampelisca abdita
Unciola irrorata
Aricidea catherinae
Ampelisca sp. X
Apoprionospio dayi
Mediomastus (LPIL)
Ampelisca macrocephala
Mercenaria mercenaria
Odostomia gibbosa

GROUP 4

Tharyx acutus
Asabellides oculata
Nucula proxima
Edotia triloba
Nephtys picta
Phyllodoce arenae
Ilyanassa trivittata
Apoprionospio pygmaea
Dispio uncinata
Spiochaetopterus oculatus
Magelona papillicornis
Euspira heros
Acanthohaustorius shoemakeri
Microprotopus raneyi
Turbonilla interrupta
Americamysis bigelowi

GROUP 5

Glycera dibranchiata
Mitrella lunata
Harmothoe imbricata

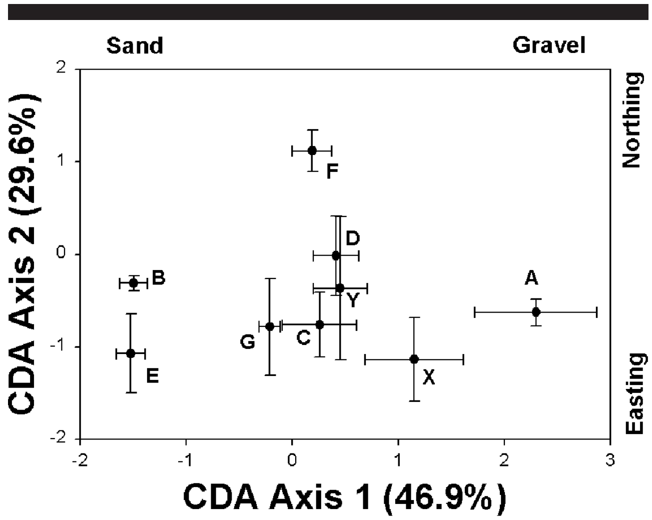

Figure 10. Means (± standard errors) of canonical variables for infaunal Station Groups A through G plotted on Canonical Discriminant Analysis (CDA) Axes 1 and 2.

steep shoreface profile along the northern New Jersey coast. During extreme wave conditions (*e.g.,* a 50-yr storm), wave height changes from borrow site excavation increased less than 10% relative to existing conditions. Hurricane simulations illustrated greater impacts along beaches south of Little Egg Inlet due to the orientation of borrow sites relative to the shoreline, whereas a northeast storm simulation generated greater impacts landward of Areas C1 and F2.

Overall, borrow sites within Areas A1 and A2, located offshore Townsends Inlet, had a greater impact on the wave field due to larger extraction volumes (8.8 and 8.6 MCM, respectively). In addition, regions with multiple borrow sites (Grids A and B2) indicated a greater potential for wave modifications with simultaneous dredging. However, the impact caused by potential offshore sand mining during normal and storm conditions was minimal.

Mean flow offshore New Jersey was to the southwest along inner shelf bathymetric contours. Strongest flow was observed in the along-shelf direction, and currents were dominated by wind-driven processes. Wind-driven processes were greatest in winter; however, flows appeared strongly biased by singular events, such as local storms. While no large-scale predictive circulation models were developed to quantify the effects of mining in sand resource areas, analysis of current patterns in the study area suggests sand mining will have negligible impact on large-scale shelf circulation. Sand mining locations are small relative to the entire shelf area, and it is anticipated that dredging will not remove enough material to significantly alter major bathymetric features in the region.

Borrow site infilling rates increased from north (Area F2) to south (Areas A1 and A2) and ranged from about 10,000 m^3/yr to 160,000 m^3/yr. This increase in potential transport rate reflects a more dynamic offshore environment seaward of the southern barrier island chain. For the water depths and proposed geometries at selected borrow sites, minimal impacts to waves and regional sediment transport are anticipated during infilling. Volume and type of sediment that replace excavated sand from borrow sites will fluctuate based on location, time of dredging, and storm characteristics following dredging episodes. However, infill sediment is expected to reflect surface sediment texture at adjacent ridge and swale deposits.

Potential effects of offshore sand mining on nearshore sediment transport patterns are of interest because dredged borrow sites can intensify wave energy at the shoreline and create erosional hot-spots. Comparisons of average annual longshore sediment transport potential were performed for existing and post-dredging conditions to indicate the relative impact of offshore sand mining on transport processes. For average annual conditions, the difference between existing and post-dredging conditions ranged from about 7% along southern New Jersey beaches to about 20% of the mean transport rate along Long Beach Island. Because the net longshore sediment transport rate predicted landward of Area C1 (Long Beach Island) was relatively low (approximately 45,000 m^3/year; similar to CALDWELL [1966]), the percentage difference between existing and post-dredging conditions was greatest for this site. Results from analyses of a 50-year event indicated similar trends.

KELLEY *et al.* (2004) developed an analytical approach for quantifying the significance of potential physical environmental impacts associated with offshore sand mining. The approach incorporates an analysis of nearshore wave transformation and wave-induced longshore sediment transport for existing and post-dredging conditions relative to temporal and spatial variations in local wave climate. Based on wave transformation results and the natural variability of normal wave climate for coastal New Jersey, predicted changes in longshore sediment transport rates resulting from offshore sand mining (up to 7 to 20% of existing conditions) are expected to have minimal impact along the shoreline for the selected borrow site characteristics. Alternative conditions are not expected to pose any greater effects unless borrow site geometries are substantially different and the quantity of sand mined from a site is larger than volumes selected for this study.

Benthic Infaunal Characterization Surveys

There was variability in infaunal assemblage composition within and between resource areas, but not uniformly across the study area. Multivariate analyses found that assemblage composition at stations in the northernmost areas (F1 and F2) was similar within and across surveys while southern areas (A1, A2, C1, G1, G2, and G3) had varied assemblages regardless of survey. Infaunal distribution and abundance correlated best with the relative percentages of gravel and sand in surficial sediments. Broad patterns of a homogeneous assemblage in northern areas and mixed assemblages in southern areas may have been due to sediment type distributions, which were mostly gravel stations in F1 and F2 and a mixture of gravel and sand stations in southern areas. Identified sand (Species Group 1) and gravel (Groups 2 and 5) taxa were common types in the region (STEIMLE and STONE, 1973; PEARCE *et al.,* 1981; STEIMLE, 1982; CHANG *et al.,* 1992). Furthermore, station groups with relatively consistent sand or gravel sediments had better defined assemblages than station groups that included both sand and gravel stations. After sediments, relative resource area location within the study area correlated best with assemblage composition, but this also may have been a reflection of sediment type distributions.

Univariate community statistics also revealed differences in assemblages comparing northern and southern areas. Taxa richness was similar across surveys in F2 but increased from May to September in other resource areas, particularly A1, A2, G1, G2, and G3. While several sand stations in G1, G2, and G3 clustered with the northern area stations in September, other southern sand stations (Group D) yielded a common assemblage that was not present in C1, F1, or F2.

Univariate and multivariate analyses of sand and gravel samples suggest that factors other than sediment characteristics also were influencing community patterns. Other possible factors include settlement and post-settlement mortality, and organic content (food supply) of sediments. It is unknown if larval settlement occurred unevenly across the study area prior to September or if settlement perhaps was spatially consistent but post-settlement survivorship or dispersal was variable. A review by ÓLAFSSON *et al.* (1994) concluded that recruitment limitation (*i.e.,* larval availability) is not the dominant determinant of infaunal community patterns in marine sediments. Instead, post-settlement processes resulting in early mortality play a more significant role in population regulation and community organization (ÓLAFSSON *et al.,* 1994; GOSSELIN and QIAN, 1997). A requisite precursor to post-settlement processes, such as competition, predation, and starvation, is faunal dispersal. It is not known at what spatial scales larval distribution may be limiting in the study area, but dispersal range probably varies between species. Studies of sessile marine invertebrate distributions have found evidence of the effects of settlement and early post-settlement mortality at small spatial scales, but mortality has less influence at larger scales (HUNT and SCHEIBLING, 1997).

Area C1 is more than 30 km and A1, A2, G1, G2, and G3 are more than 60 km south of Areas F1 and F2. GRAY (2002) suggested that climatic, latitudinal, or other prime forces regulate broad-scale patterns of infaunal species richness, but regional habitat characteristics (*e.g.,* sediment grain size) probably influence variability over smaller scales. Wave transformation modeling and analysis of sediment transport rates indicated differences between the northern and southern portions of the study area. Southern resource areas also are in proximity to several coastal inlets (*e.g.,* Little Egg Inlet) that are potential sources of organic material. Periodic nutrient inputs to inner shelf sediments can promote intermittent levels of secondary production that otherwise are non-sustainable (HANSON *et al.,* 1981; TENORE, 1985). Substantial additional evidence indicates that secondary production of soft-sediment benthos often is limited by food supply (ÓLAFSSON *et al.,* 1994). In addition to sediment regime, other physical environmental differences between northern and southern portions of the study area may have affected infaunal community patterns.

This study provides infaunal community characterization and does not include post-dredging monitoring. Reviews of prior studies are useful for deduction of general mechanisms of recolonization and recovery in offshore dredged sites (VAN DOLAH, 1996; NEWELL *et al.,* 1998). Frequent benthic disturbance favors opportunistic infaunal taxa (GRASSLE and GRASSLE, 1974; MCCALL, 1977). However, later successional stages of benthic recolonization tend to be more gradual, and involve taxa that generally are less opportunistic and longer-lived. In mined areas with prolonged effects to the infaunal community, transitional opportunists tend to persist (WILBER and STERN, 1992), and it is the later successional stages that may not fully recover for 2 to 3 years. Long-term consequences of sediment mining become more likely in relatively steep bathymetric depressions that sometimes are formed by dredging (NATIONAL RESEARCH COUNCIL, 1995). Such depression features often show increases in silt and clay following dredging (BURLAS *et al.,* 2001). In a borrow site located 3.6 km offshore Coney Island, New York, a prominent bathymetric depression was formed by dredging, and alteration of infaunal assemblage composition at the site has persisted for nearly a decade because of silt settling in the site (BARRY A. VITTOR & ASSOCIATES, INC. STAFF, 1999).

Assuming that smoothly graded features are created by dredging, recolonization by opportunistic taxa, and perhaps later successional stages, may occur in concert with recruitment processes in adjacent non-dredged areas. Strategically dredging portions of target shoals in resource areas could increase the likelihood that motile adults are available for migration into dredged areas from adjacent sediments (VAN DOLAH *et al.,* 1984; JUTTE *et al.,* 2002). GÜNTHER (1992) concluded that post-larval and adult migration into disturbed areas becomes less important, and larval settlement more important, as size of a disturbed area increases. Presumably this is due to currents or other physical forces that disperse pelagic larvae across greater distances than motile post-larvae or adults that crawl or burrow. Mining several small sites on a target ridge or shoal, or mining relatively small portions of several ridges or shoals, may help to ensure availability of nearby populations of potential colonizers. Variations in biological and physical processes along the New Jersey shelf may differentially influence larval settlement and adult immigration. If physical and biological differences between northern and southern portions of the New Jersey shelf are real, the nature and duration of benthic effects may differ with location of mined sites.

CONCLUSIONS

Nearshore sediment transport analyses performed and simulations conducted for potential sand mining operations on the New Jersey OCS have identified minor physical environmental impacts. However, under normal wave conditions, the average change in longshore sand transport was about 10% of existing conditions. Based on wave transformation results and natural variability of the normal wave climate for coastal New Jersey (see KELLEY *et al.,* 2004), predicted changes in longshore sediment transport resulting from offshore sand mining are expected to have minimal impact along the shoreline. Although changes during storm conditions illustrated greater variation, the relative impacts were similar to non-storm conditions. Furthermore, the ability of models to predict storm wave transformation and resultant sediment transport is less certain than for normal wave conditions.

Impacts to the benthic community are expected due to physical removal of borrow material and infauna. Based on previous studies, and assuming that dredged sites do not create a sink for very fine sediments or result in hypoxic or anoxic conditions, levels of infaunal abundance and diversity may recover within 1 to 3 years, but recovery of species composition may take longer. The nature and duration of benthic effects may differ with location of mined sites, due to physical and biological differences between northern and southern portions of the New Jersey shelf.

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