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An Investigation of Potential Consequences of Marine Mining in Shallow Water: An Example from the Mid-Atlantic Coast of the United States[1]

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ABSTRACT

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Proper stewardship of the coastal marine area necessitates consideration of the potential environmental consequences of marine mining. Such a study would include investigation of the benthic infauna, commercial and recreational fisheries, sea turtles and marine mammals that utilize the area to be mined, anticipated changes in wave transformation, storm surge, and bottom currents, and the history and dynamics of shoreline change. A case study on the U. S. mid-Atlantic coast offshore of Maryland and Delaware indicates that the consequences of a sand-mining project, on the order of 2×10^6 m^3 would be relatively minor whereas the results of a larger project or cumulative removal of 2.4×10^7 m^3 likely would substantially greater but should not be prohibitive.

ADDITIONAL INDEX WORDS: *Sand-mining, environmental assessment, Maryland, Delaware.*

INTRODUCTION

The suite of scientific investigations associated with possible marine sand-mining is a multi-disciplinary package of efforts requiring frequent interaction amongst the participating scientists. If the research is expanded beyond scientific study of the potential impacts to include effects upon the shore, engineering and economic considerations, and, perhaps, regulatory aspects of the proposed resource utilization, the set of investigations involves significant interaction amongst persons with different expertise and outlook. Recent comprehensive studies related to marine sand-mining for beach nourishment in Virginia, Maryland, and Delaware and in other generic studies serve as examples of the types of individual studies and cooperative efforts necessary before undertaking a physical modification of the marine environment. In the future, as the demand in portions of North America for construction aggregate outpaces conventional land-based resources, the demand for marine resources of sand and gravel likely will increase as it has in parts of Europe and Japan (MARSHALL, 1990).

The CORPS OF ENGINEERS (1995) approaches the question of potential impacts associated with sand-mining with an outline of procedures to be followed when conducting an assessment of sand resources. However, this short document emphasizes determination of the suitability of the sand body, barely addresses biological constituents, and does not consider any physical consequences of modifying the topography of the sea floor. SMITH (2000) states "research into the potential consequences of dredging from the offshore seabed, (sic) is still within its infancy." He further indicates that several aspects of the targeted deposit, including its genesis and stability, must be understood before it should be mined.

The root of the potential problems is the simple act of disturbing the natural sea floor. The disturbance usually is in the form of an excavation. Even if the excavation is only centimeters deep, it will have a profound effect on the resident infauna and lesser, but none-the-less real, consequences on the local pelagic organisms and physical processes. The biological impacts are a function of the surface area of the disturbance whereas the physical impacts are functions of both the surface area and depth of disturbance.

Although not addressed in this paper, post-disturbance monitoring of mined sites is an essential component of the overall study. A formal monitoring program likely is the only means by which data can be obtained with which to assess the accuracy of the pre-dredging assessments. SCHAFFNER and HOBBS (1992), HOBBS (1993), and SCHAFFNER *et al.* (1996) indicate some of the elements that must be considered in such a monitoring study.

Biological Oceanography

The logical working assumption is that all of the infauna within the sediments that are dredged will die. Hence, before an area might be excavated, there should be an inventory or assessment to determine the types and quantities of organisms, or, put another way, the species diversity and biomass, that would be lost should the project be performed. In an early stage of project design, the benthic ecologists should be employed to map, characterize, and quantify the biological

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community. Determination of some sort of resource value and a comparison with probably post-dredging conditions is appropriate.

The biological assessment of the potential dredging area has two additional and important aspects: the recolonization potential of the area and likely consequences on the pelagic, or transient, fauna. In order to make a reasonable assessment of the recolonization of the dredge area, the biologist must have input from the geological and physical oceanographers as well as from the project design engineers. The engineers should indicate the proposed method and plan for dredging (type of equipment, depth of excavation, and whether the removal will in the form of a hole or a shallow scraping off the surface); while the geologists should indicate the granulometric nature of the final substrate. The often forgotten aspect is the projection of the changes in physical dynamics. The physical oceanographer should forecast the bottom agitating forces that will act on the area after the dredging project is complete. Collectively, these elements will exert a substantial control on recolonization.

The biology of the water column warrants review and consideration, though the potential impacts are less acute. It is necessary to have thorough knowledge the regional fisheries resources - What species, at what stage(s) of their lives, larval, mature, spawning or not, inhabit the area and when they do so. The changes in infauna might impact the available food resources. Spawning characteristics might argue for seasonal restrictions on dredging *etc.* For the species that utilize the area, is there a formal Fisheries Management Plan? Has the area been designated part of an Essential Fisheries Habitat? Are there important recreational or commercial fisheries? The two other major members of the nekton that must be considered are sea turtles and marine mammals. The actual mechanical act of dredging and, in the case of turtles, pumping sand onto the beach are the items of concern.

In most instances, the only actual field work that the biologists will have to conduct is mapping the infauna and related characteristics such as sediment type and depth to the Redox Potential Discontinuity (RPD). Regional data on the nekton that transit the area should be available in the literature but it is unlikely that there are sufficient site-specific data on the bottom dwelling organisms. Also, depending upon the gross, regional location, repetitive surveys will have to be conducted in order to evaluate seasonal and, perhaps, interannual variations in community make-up and density.

Physical Oceanography

Physical oceanographers will need to determine the direct impacts of altering the bottom topography on wave transformation, tidal currents, and storm surge and the indirect impact on bottom shear stress and other benthic boundary processes which influence both biota and sediment transport. Wave transformation processes include refraction and diffraction as they relate to wave height, bottom disturbance, and breaking wave height and, sometimes, direction as it drives longshore sediment transport. These determinations are the outputs of various numerical models. The physical oceanographers would run the models with identical input conditions for the existing bottom bathymetry and for a limited set of cases in which the bathymetry has been modified to depict likely dredging scenarios. Should one of the goals of the overall study be an analysis of the impacts of dredging on the future evolution of the morphology of the sea bottom, the physical oceanographers will need to work with geological oceanographers to adapt or develop appropriate models. These models would need to integrate agitation of the bottom surface, sediment resuspension and mobilization, and rates and directions of sediment transport yielding sites and rates of erosion and deposition. The model would need to be run through many iterations as the output of one run would be a set of changed bottom conditions that would cause slight differences in the results of the next model run.

One of the critical pieces of information to the modeler is the present depth of water over the area(s) that are postulated for dredging. As the depth increases so to does the minimum wave height required for the wave to "feel" bottom with the consequence that for deeper water dredging sites there are fewer wave conditions that might need to be modeled. With any good luck, there will be sufficient regional data on depth, winds, waves, and currents that the physical oceanographers will not have to undertake a substantial field program.

NOAA's National Ocean Survey, or its predecessors, have compiled bathymetric data for most of the populated coastal areas. Generally these data are available on CD-ROM and can be manipulated into the specific format required for the model being run. Similarly wave and, sometimes wind, data are available from NOAA maintained offshore wave buoys. Long periods of record are necessary if the frequency of rare, high energy events is to be considered in the characterization of the regional wave climate. If at all possible, at least a decade of record should be used. In addition to data from offshore buoys, it is a substantial help if there is a record from the nearshore. Using conditions recorded offshore as input to a wave transformation model and comparing the model's output with near simultaneous data from the nearshore record, it is possible to calibrate the numerical model of wave transformation.

Analysis of a long period of observations (~10 years) allows for the development of wave frequency diagrams and the sorting of waves into bins based upon height, period, and direction. If suitable wave data are not available, it will be necessary to use historical weather data and develop a hindcast wave climate. These data, in turn, can be selected to exclude wave conditions that either will not experience altered transformation due to bottom modification or are directed offshore and will not have an impact on the shore.

Geological Oceanography

The geological oceanographer's role is complex and, perhaps, less easily defined that some of the others. The geologist has a key role the early stages of the project by defining and proving the sand resource. Along with coastal engineer, the geologist can assess the geotechnical (*e.g.,* grain size) requirements for a beach nourishment project, compare those with the characteristics of the resource, make initial estimates of over-nourishment needs *etc.* The geologists and engineers also need to work with the physical oceanographer's wave data to estimate the direction and scale of longshore sediment transport and the resultant impacts on shoreline form. Through studies of historical shore morphology, both cross shore profiles and along shore form, the coastal geologist provides information that will be essential in estimating and then gauging the success of the nourishment effort.

APPLICATION

The U. S. Department of the Interior's Minerals Management Service (MMS) is the official steward of the mineral resources under U. S. federally controlled waters—generally those waters more than 3 n.mi. (~5 km) seaward of the shoreline. In addition to "simple" permitting, including potentially collecting fees, to allow sand mining, the MMS includes evaluation of the potential environmental consequences of sand mining as part of the duties required by its role as steward. To that end, MMS has funded a series of studies of potentially exploitable sand resources off the East and Gulf Coasts of the U.S. The initial study of the sand resource offshore of Virginia Beach, Virginia (HOBBS, 1998) served as a prototype upon which studies in Alabama (BYRNES and HAMMER, 1999), New Jersey, Delaware, Maryland, North Carolina, South Carolina, and Florida have been based (the later projects are in progress at the time of writing). Additionally, MMS funded a general environmental study for sand resources offshore of New Jersey, Maryland, Delaware, and Virginia (THE LOUIS BERGER GROUP, INC., 1999). Generally the sea floor within the "3 n.mi. limit" is managed by the state government; each state having different procedures and requirements.

The following discussion of the Maryland-Delaware project (Figure 1) is an example of the range of studies encompassed in the preliminary consideration of potentially using a region's submarine resources of sand. The work emphasizes the large ridges, Fenwick, Isle of Wight, and Weaver Shoals, especially the first two, that lie about 5 km east and then south of the Delaware-Maryland border. This is because the ridges appear to be logical targets for exploitation.

Fisheries

Fisheries scientists were able to work independently of the other disciplines and conduct thorough reviews of the literature to identify potential problems and to describe the potential seasonal conflicts (MUSICK, 1998; OLNEY and BILKOVIC, 1998). A relatively new "problem" or consideration is the designation of substantial areas of the continental shelf as "essential fish habitat" (EFH) for several individual species. Although any one individual sand-mining project likely would affect only a small area, probably a fraction of one percent of any EFH, the conflict still must be addressed.

MUSICK (1998) reviewed three broad groups of transitory, vertebrate nekton likely to pass through potential mining areas offshore of Maryland and Delaware: fishes, turtles, and marine mammals. He concluded that the very small size of the areas likely to be dredged relative to large geographic ranges of the transitory fishes indicates that sand mining would have little impact on fish populations. Additionally, the potential threat to sea turtles can be minimized by mining from mid-November to mid-April when these subtropical animals are absent from the area. Finally, he concluded that sand mining poses no foreseeable threat to the migratory and highly mobile marine mammals.

OLNEY and BILKOVIC (1998) assessed the reproductive fishes and ichthyoplankton within the study area. They determined that at anytime during a year some species were present in spawning, egg, and larvae stages (Figure 2). The fewest species are present during the winter months, January, February, and March, though the window of low reproductive species occurrence appears to extend from December to, perhaps, mid-April.

Benthic Biology

CUTTER and DIAZ (2000) performed an assessment of the existing community structures, spatial distributions, substrate dependencies, productivity, and trophic linkages in order to anticipate the consequences of sand mining upon the biological resources of the area. These subjects should be considered with respect to the scales and magnitudes of normal environmental stressors and the potential for interference with these dynamics.

The primary data on which this set of studies is based were obtained during the course of research cruises in 1998 and 1999. Instruments used on either or both cruises included a standard "Young" grab with a 0.044 m^2 surface area for sediment samples, a Hulcher model Minnie Sediment Profile camera (SPI), a standard bottom imaging sled which carried video cameras and water quality sensors, a Burrow-Cutter-Diaz Plowing Sediment Profile Camera System, a 600 kHz high resolution side-scan sonar, and a 2.4 m (8 ft) beam trawl to collect juvenile fish, epibenthos, and macrobenthos. In addition to analyses of the samples and images, the data were coded for display in a Geographic Information System (GIS).

CUTTER and DIAZ (2000) calculated the Benthic Habitat Quality (BHQ) index of NILSSON and ROSENBERG (1997) throughout the region of interest. The BHQ index can range from 0 to 16 with values of 5 and above indicating "good quality benthic habitat." In general, on the relatively featureless area offshore of Indian River Inlet, the BHQ was low and had little spatial variation. For data from the 1998 cruise, the values ranged from 1 to 8 with an average of 5. In the shoal regions, the BHQ ranged from 1 to 13 with an average of 5.6 but varied with the morphology. BHQ was lower on the crests of the shoals where agitation is greater and slightly greater in the deeper regions; although the distribution of microhabitats is more complex than suggested by that simple statement.

Biological associations with individual microhabitats are functions of substrate (primarily grain-size distribution) and energy regime. The characteristics of specific areas may vary through time in response to physical changes in the shoals. Thus anthropogenic modification of the shoals, as would result from sand mining, would alter the benthic habitats. Also the season(s) in which sand mining took place would affect recolonization as function of the life history stage of the ben-

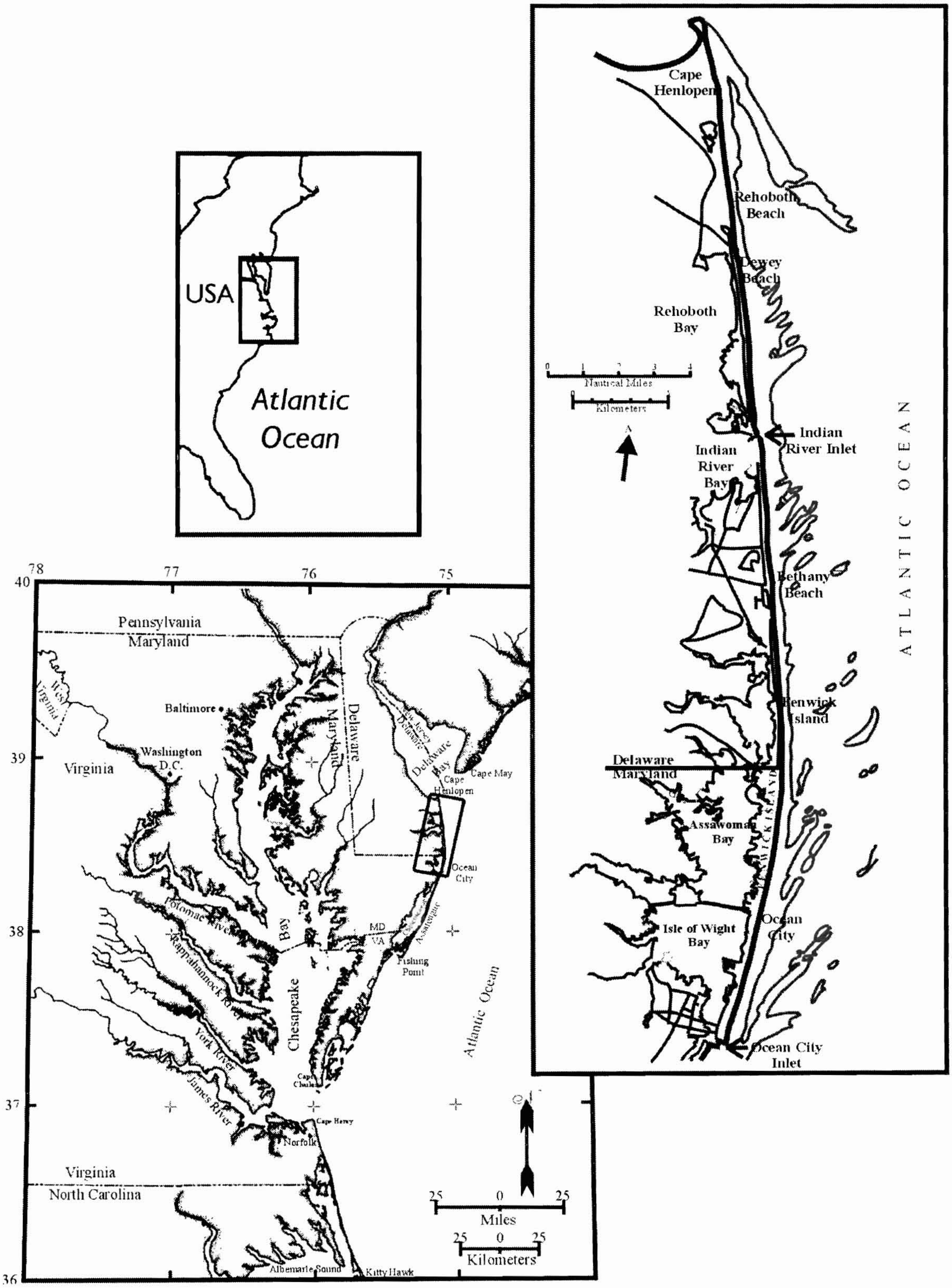

Figure 1. Location of the Maryland-Delaware study area.

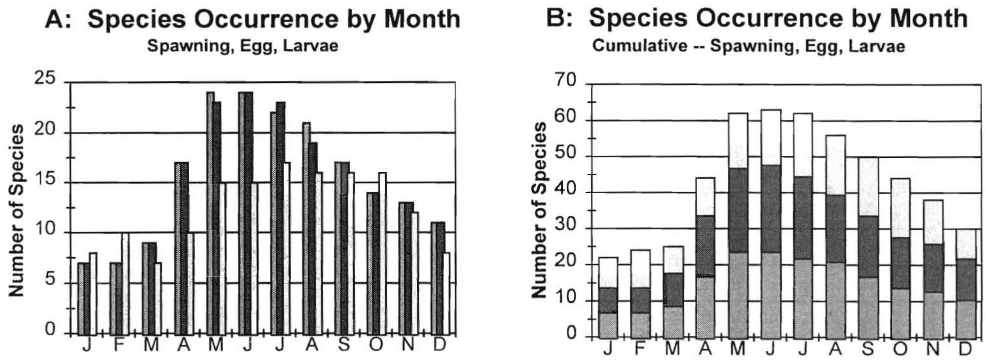

Figure 2. Species occurrence, spawning, egg, larvae, within the study area by month. A) by life stage, B) cumulative.

thic organisms. Recruitment of larvae and juvenile stages of animals likely would be quicker in spring-summer while recruitment of adults likely would be regulated by factors, such as storms, that affect passive transport.

In order to ensure that the biological assemblage that recolonizes a mined area resembles that prior to mining, it would be beneficial to avoid total stripping of the surface. By leaving small "islands," "refuge patches," within the sand mining area, local resident-species would more easily be able to recolonize the nearby disturbed sections resulting in a post-mining assemblage that generally should be like the earlier condition.

The alteration and recovery of a benthic biological community from a disturbance such as sand mining likely will be dependent upon waves, currents, and bottom stresses in the period immediately subsequent to mining. Therefore the consequences of sand mining could be substantially different if a long period of calm or a major storm closely followed the dredging.

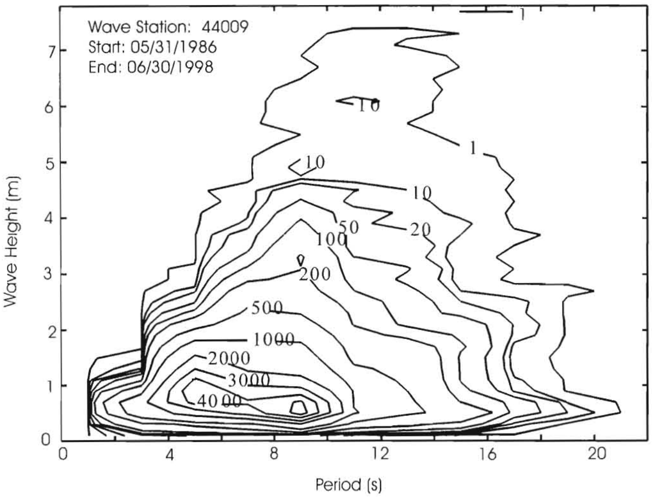

Figure 3. Joint distribution of significant wave height (m) and peak energy wave period (s) at station 44009 (from Maa and Kim, 2000).

Physical Oceanography

Maa and Kim (2000) analyzed a set of existing physical oceanographic aspects and modeled how conditions might change following sand mining. The work addressed changes in waves, storm surge, tidal currents, and bottom stress resulting from dredging on Fenwick and Isle of Wight Shoals. The wave analyses considered two dredging scenarios: mining of approximately 2×10^6 m^3 from each shoal and a total removal of 2.4×10^7 m^3. The model was run using an unmodified bathymetry to establish base conditions then run again using a post-dredging bathymetric scenario.

For driving conditions and calibration, the study used wave data from a wave buoy maintained by the National Data Buoy Center, station 440099, located about 40 km offshore of Ocean City and from two nearshore stations maintained by the U.S. Army Corps of Engineers. During 13 years of observations at the offshore station, the maximum significant wave was 7.6 m with a period of 16.7 s which occurred during a January storm, or northeaster, not during a hurricane. Review of the data (Figure 3) resulted in selection of 60 waves from among four wave heights (2, 4, 6, and 8 m), five periods (10, 12, 14, 16, and 20 s) from seven general directions (NNE, NE, ENE, E, ESE, SE, and SSE). Because short period waves (less than 10 s) do not affect the shoals, they were not considered even though they have a relatively high frequency of occurrence. The bathymetry input to the model was taken from NOAA sources.

The REF/DIF-1 wave transformation model was selected over several other models (SWAN, HISWAP, STWAVE, and RCPWAVE, among others) following a comparison of the different model's strengths and weaknesses (Maa *et al.*, 2000). The wave model was calibrated by comparing conditions synoptically observed at the offshore and inshore wave stations with calculated or modeled data for the inshore stations using the observed offshore data as input. The variable model parameter representing bottom friction was adjusted so that the model's output most closely resembled the observed conditions.

In addition to providing base-line information, running the wave transformation model with a unmodified bathymetric input provided an ability to compare the present distribution of wave energy with the condition of the shoreline. In general the relatively stable region of the shoreline around the Maryland-Delaware boundary coincides with an area of diminished wave energy and the more erosive sections near Ocean City appear related to local concentrations of wave energy.

Comparisons of results from model runs with the unmodified bathymetry with runs in which the removal of approximately 2×10^6 m^3 from each shoal indicates that there would be relatively little change in the wave environment. However a total mining of 2.4×10^7 m^3 would result in an increase in wave height in the area between the dredge sites and the shoreline. Evaluation of the impact of this increase on the shore is difficult.

The potential impact of dredging on storm surge was assessed with a standard computer model (SLOSH - Sea, Lake, and Overland Surges from Hurricanes)(Jelesnianske *et al.,* 1992). The model was run with the unmodified bathymetry and the bathymetry after the 2.4×10^7 m^3 mining scenario. Using a modeled, category 4 hurricane and two storm tracks, one generally shore parallel, the other shore normal, there were negligible, almost nonexistent, differences between the pre- and post- dredging outputs.

The natural tidal currents in the area are fairly low, approximately 20 cm/s at the surface decreasing to around 5 cm/s at the bottom except slightly greater, 5–10 cm/s, over the shoals. Modeling indicates that the cumulative dredging scenario would result in an increase of approximately 10 percent in the bottom currents. As this translates to an overall increase on the order of 1 cm/s, the impact of dredging on bottom currents is considered to be very small.

Finally, yet another computer model, an adaption of the Grant-Madsen-Glenn model (GRANT and MADSEN, 1979, 1986; GLENN and GRANT, 1987) was used to assess changes in the combined wave and current generated bottom disturbing forces. Again, the impacts of dredging appear minimal.

Coastal Geology

HARDAWAY *et al.* (2000) reviewed the recent geologic history of the coast with emphases on changes in shoreline position and possible influences of works intended to stabilize the shore. The approximately 100 km long coastal region between Ocean City, Maryland and Cape Henlopen, Delaware is the product the sea rising across a young, sedimentary substrate. The recently eroded, underlying, and presently eroding strata were formed in very similar environments as the ocean moved back and forth across the coastal plain in response to sea level changes resulting from global changes in glaciation during the Quaternary. The shoreline is a wave (or storm) dominated, micro-tidal (mean tide range about 1.1m) system that has experienced approximately 30 cm of sea-level rise over the past century. BOSMA and DALRYMPLE (1997) characterize most of Delaware's Atlantic coast as being in a state of erosion. Although natural processes operating along an open coast tend to straighten the shoreline, the actual form of the shoreline depends, in part, on the geology of strata both being and recently eroded. Bluffs, dunes, barrier spits, marshes, and inlet associated areas all respond differently and leave different physical remnants on the post-erosion, flooded sea floor. Modern "hot spots," sites of chronically greater erosion, appear to be related to patterns of wave refraction which is a function of the overall wave climate and the location of offshore shoals.

The jetties at Ocean City Inlet, the southern limit of the study area, and Indian River Inlet have had substantial local impact since their construction and indicate a spatial change in condition along the coast. The area south of Ocean City Inlet, although heavily modified by the jetties, in not part of the present study. The net longshore littoral drift near Ocean City flows southward and has built a substantial fillet of sand against the north jetty whereas the net drift at Indian River Inlet is toward the north. The area south of Ocean City Inlet although heavily affected by the jetties is not part of the present study. A permanent sand-bypassing plant at the Indian River Inlet serves to feed the longshore drift and deposits sand to the north of the inlet. The nodal zone, or region of current reversal, appears to be around the Delaware-Maryland border. Many sections of the shore have been modified with sea walls or bulkheads and groins. During the past two decades, there have been several substantial episodes of beach nourishment. VALVERDE *et al.* (1999) list 41 beach nourishment projects in Delaware between 1963 and 1994 for a total of over 5.9×10^6 m^3 at a minimum cost of $\$16 \times 10^6$, adjusted to constant 1996 dollars. (They could not document costs for several projects). They also listed 6 projects in Maryland for 7.8×10^6 m^3 and $\$51 \times 10^6$. Individual nourishment projects ranged from a privately funded $20,435 for 3,650 m^3 to a $10,800,000 federal project of 2.88×10^6 m^3. The MARYLAND GEOLOGICAL SURVEY (2000) estimates that beach nourishment at Ocean City, Maryland will require 9.2×10^6 m^3 of sand within the next 50 years.

The long term history of the shore is one of retreat. Comparisons of maps and charts from 1850 with modern map, chart, and photographic data document a receding shoreline and a transgressing sea. According to HARDAWAY *et al.* (2000), the rate of retreat shows both spatial and temporal variability. Analysis of recent beach profiles suggests that although the actual shoreline (*i.e.* the intersection of the physical shoreface and a tidal datum such as mean high water or mean sea level) may be retreating, sand eroded from landward portions of the beach might be accumulating in the shallow nearshore, especially in the vicinity of sections that have been nourished. If this is so, even though the sand has been lost from the accessible, recreational beach, it still is part of the beach-shoreface system and might be serving to protect the inshore portions of the shoreface from larger waves. The veracity of this supposition should be tested through a carefully designed, consistent, long term program of monitoring the condition of the shore zone.

CONCLUSIONS

Although there are potentially adverse consequences to sand mining in the offshore regions of Delaware and Maryland, they likely are not substantial and actions can be taken to minimize them. Obviously dredging the bottom destroys all the organisms that had lived within the dredged area, but the best sands for beach nourishment have a comparatively low resource value. The benthic fauna of those areas are likely to recolonize fairly rapidly especially if small "islands" are left untouched within the otherwise dredged area. Care should be taken to minimize disturbance of the substrate between the shoals that will be the targets for dredging. The very small size of the areas likely to be dredged relative to the large geographic ranges of transitory fishes indicates that sand mining would have very little impact on the fish populations. The species occurrence of fishes in spawning, egg, and larvae stages is least from October through March and peaks in the late spring and summer. The potential threat to sea turtles can be avoided by mining from mid-November to mid-April when these sub-tropical animals are absent from the area. Sand mining poses no reasonably foreseeable threat to the migratory and highly mobile marine mammals.

Analysis of existing wave conditions demonstrates that modern shoreline stability is related to areas of concentration and dispersion of wave energy near the zone of breaking waves. The relatively stable area around the Maryland-Delaware border is one of relatively low waves whereas the various erosional "hot spots," especially along Fenwick Island, appear coincident with zones of wave energy concentration. Wave transformation modeling indicates that removal of 10^6 m^3 of sand from the top of Fenwick and Isle of Wight Shoals will result in very small changes from present conditions. Removal of 10^7 m^3 might cause more noticeable changes in the regions between the dredged areas and the shore. Modeling also predicts that dredging will have an extremely small impact on ambient tidal currents and potential storm surges.

The Maryland-Delaware shore is experiencing increasing pressure from expanding recreational and residential uses and the associated commercial developments. The form of the shoreline results from interactions amongst the local geology and stratigraphy, the history of Holocene sea-level rise, and the contemporary wave climate. Although rising sea level drives a general marine transgression/shoreline retreat through the area, the rate of retreat and apparent local stability vary along the shore. Shoreline engineering, most noticeably sand bypassing at Indian River Inlet and repetitive beach nourishment at several sites, has been employed to control shoreline retreat and enhance the recreational value and use of the beach. The cumulative impact of the many beach nourishment projects that already have been performed appears to be more beneficial than any individual project.

The scope of studies described in the Maryland-Delaware example is indicative of the range of research that should be performed in an area considered as a potential site for marine mining. However, investigation of potential consequences is only part of the work necessary to evaluate a marine mining project. Should the mining project go forward, it is important that it be followed with a vigorous, multifaceted, coherent monitoring program. Unless the post-mining conditions are assessed and measured, the validity of the pre-mining predictions cannot be evaluated. It is this evaluation that will allow the improvement of predictions for future projects.

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