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Impact of Dredge Spoil Disposal on Benthic Communities in the Delaware Estuary

A White Paper Report

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by

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Executive Summary

Concerns have been raised over the impact of dredged sand stockpiling as part of the Army Corps of Engineers' Delaware River Main Channel Deepening Project. Particular questions relate to the adequacy of previous studies for sampling benthic communities and to the lack of consideration of the impact of spoil disposal on these communities. The overall objective of this report is to compile what is known with regard to specific, identified issues concerning dredge spoil disposal and sand stockpiling in the Delaware Bay. The primary resource for this report was the published literature identified through the University of Delaware's library holdings and searchable electronic databases.

Library catalog and on-line searches uncovered numerous studies of the ecology of the bay. Much of the work focuses on Delaware Bay plankton (e.g., blue crab larvae) or finfish. Benthic studies have focused either on certain sites (e.g., Cape Henlopen) or fauna (e.g., oysters and horseshoe crabs) of particular interest. Because of their broad geographic coverage and, in particular, their use in support of impact assessments, the work of Maurer et al. in the early 1970s and the more recent sampling as part of the EMAP-E Virginian Province program were both selected for detailed consideration. Since these surveys were limited by sampling gear to soft-bottom habitats, a separate discussion of important hard-bottom habitats is presented.

Based on this summary of existing information on the bay's benthic communities, additional questions relevant to the dredging project are addressed. The conclusion of "no significant impact" presented in the January 1997 Supplemental Environmental Impact Statement (U.S. Army Corps of Engineers 1997, hereafter denoted "SEIS") is criticized on eight separate points. While the arguments presented in the SEIS are not without merit, they miss the point that there are hard-bottom communities located in the general area of the proposed sand stockpiling sites. These were not adequately sampled in the field and thus were not considered in the SEIS analysis.

A critical analysis of the existing survey data is also made. Since sampling devices used in conventional benthic sampling work poorly on hard bottoms, there is an intrinsic gear bias in the surveys. This represents the greatest limitation inherent in the existing data sets.

It is reasonable to assume that emplacement of spoils will smother the benthic community and bury it, resulting in the death of all individuals and a defaunation of the bottom at the site. This prediction should hold regardless of the engineering details, existing bottom type or community, or type of disposal material. While short-term effects of spoil emplacement on benthic communities are clearly catastrophic, recolonization of the defaunated area will permit long-term reestablishment of a benthic community, although perhaps different from that prior to spoil disposal. The time to reach a new, stable community is likely to be months or longer, depending on the seasonal recruitment of many species. Lateral migration of fauna from nearby undisturbed areas by crawling, burrowing, swimming, or transport by tidal currents or wave action will facilitate recruitment in defaunated areas and aid in reestablishing communities typical of those in the area. The hydrodynamic regime and emplaced sediment characteristics are both important determinants of the new, eventual benthic community type.

The best sites for spoil emplacement would be those resulting in minimal changes in sediment grain size, water depth, and benthic community composition. Assuming that some alteration is unavoidable, smaller affected areas would more quickly recover and be more like surrounding benthic communities. Since spoils are unconsolidated soft sediments, disposal should be in areas away from, and with little or no expected transport to, hard grounds. To minimize the total area affected over many years or projects, disposal sites should be reused to the fullest extent possible.

This white paper analysis reviews the literature on the bay's benthos, assesses its adequacy for spoil disposal project evaluation, reassesses possible impacts, and suggests mitigation strategies. Within these areas, several questions arise that could be addressed by field-oriented research. The hard-bottom habitats of the bay need to be characterized in terms of their general distribution and species composition. With specific reference to the reef-like conglomerations of worm tubes known as "worm rocks" and "coral beds" and their associated fauna, important questions include the susceptibility of the worm colonies to burial during construction activities and by sand (or fine sediment "clouds") subsequently redistributed by storm waves and tidal action. It is highly desirable that all the hard-ground communities of the bay (not just those of economic interest) be mapped efficiently. Given access to the raw data of the Maurer et al. and EMAP-E surveys, it may be useful to synthesize these data sets and resolve any inconsistencies in species identification or nomenclature over the 25-year interval between the surveys. Storms and tidal currents are natural agents of sediment movement, and benthic animals are well adapted to living in a dynamic environment. It is reasonable to hypothesize that certain species or functional groups, or even certain community assemblages, will accommodate frequent, natural sediment movement, burial, and erosion. Laboratory and field experiments, from modest water-tunnel flume studies to large-scale field manipulations, could be used to study these hypotheses.

Several appendices and a list of references follow the narrative section of this report. Individual appendices include a glossary of benthic terms, a list of general reference works in benthic ecology and methods, a list of useful identification guides and keys, and a summary of database searches.

Review of Relevant Literature

The Philadelphia District of the U.S. Army Corps of Engineers has conducted studies pursuant to modifying the Delaware River Federal Navigation Channel in the Delaware Bay. This Delaware River Main Channel Deepening Project seeks to increase the channel depth by 5 feet in addition to widening bends in the channel at certain locations. An estimated 33 million cubic yards of dredged material would be removed from the channel as part of the initial construction, and the annual maintenance dredging would increase from 4.9 million to 6 million cubic yards. In Delaware Bay, dredged material from the initial construction would be used for wetland restoration at Egg Island Point, NJ, and Kelly Island, DE, and for stockpiling sand at Slaughter and Broadkill beaches in Delaware for later beach nourishment projects.

The January 1997 Supplemental Environmental Impact Statement (U.S. Army Corps of Engineers 1997, hereafter denoted "SEIS") provided additional information and environmental analysis addressing concerns raised during the review of the 1992 feasibility report. In particular, benthic invertebrate sampling was used to assess habitat quality at selected sites in the bay. Since no significant differences were found between candidate stockpile and background sites, it was concluded that no significant impact would occur due to the use of these sites for sand stockpiles (SEIS, sec. 9, p. 5). Further, no unique benthic species were identified. While the stockpiling of dredged material was expected to result in the burial and destruction of the existing benthic community, recolonization and recovery were expected to be rapid. Long-term impacts, however, would be determined more by the nature and frequency of disturbance of these sites as part of future beach nourishment projects.

Subsequently, in early 1998, additional concerns were raised over the impact of stockpiling dredged sand in the lower Delaware Bay. Specifically, these issues included the following:

- the validity of the "no significant impact" inference from prior benthic sampling,
- the adequacy of the completed survey work for assessing the benthic community, particularly hard-bottom and unique habitats like the "worm rocks" and "coral beds" (reef-like masses of hardened worm tubes and their associated invertebrates),
- the failure to consider all benthic communities in the impact assessment, and
- the expected impact on undersampled habitats and fauna, even if not located directly in the stockpile sites.

The so-called gear bias is a serious issue. Recent surveys have used sampling gear designed to retrieve organisms living within soft sediments such as sand, mud, and silt (termed infauna) rather than those living on or building structures above the bottom (known as epifauna). Grab and core samplers are inadequate for sampling reefs or hard-bottom habitats. Field crews would avoid using such gear in these habitats, and it is unlikely that epifauna would be represented accurately in the samples. Furthermore, the last comprehensive benthic sampling targeting the bay was conducted by Don Maurer and his colleagues more than 25 years ago (i.e., in 1972–73; published in, for example, Maurer, Watling, et al. 1978). Despite the wide spatial coverage of these efforts, criticisms over sampling gear and sieve mesh size call into question the utility of even this extensive data set.

Project Objectives

With regard to the impact of dredge spoil disposal in the shallow regions of the lower Delaware Estuary, the objectives of this project are

- to summarize existing information on the lower bay benthos, including hard-bottom as well as soft-bottom habitats,
- to predict impact on benthos in and near disposal/stockpiling areas, particularly those benthic communities not considered to date,
- to assess likely long-term impacts and possible mitigation strategies,
- to make recommendations for minimizing or mitigating any suggested impacts, and
- to identify research questions relevant to future, field-oriented research projects.

The findings of this study, as determined from existing literature, are presented in this final report. Within Delaware Bay, some emphasis will be placed on the benthos of the sand stockpiling sites off Slaughter Beach and the Mispillion River and off Broadkill Beach. These are the selected stockpiling sites, designated MS-19B and L-5, respectively, in the project SEIS. The worm rocks and coral beds are well known to be found in the general area of these sites.

Methodology

This is a paper study, and the primary resource is the published literature identified through the University of Delaware's library holdings and electronic searches of the Cambridge Scientific Abstracts database, *Aquatic Sciences and Fisheries Abstracts* (ASFA). This database provides citations and abstracts to the world's literature dealing with the science, technology, and management of marine, freshwater, and brackish water environments and organisms. Topics cover biological sciences and living resources, ocean technology, policy and nonliving resources, and aquatic pollution and environmental quality, plus two specialized files for aquaculture and marine biotechnology.

This electronic database encompasses primary literature, gray literature, technical reports, and Web sites as far back as 1978. For older relevant material, I worked backward through bibliographies, scanned theses and dissertations by College of Marine Studies graduates, and used the card and electronic catalogs of the University of Delaware Marine Studies Library. This library maintains an up-to-date catalog of college and Sea Grant documents, including older reports and theses central to this study.

Searches were made by keyword for various locations (e.g., Delaware Bay, Broadkill Beach), common or proper names of authors, and taxonomic names (e.g., *Sabellaria*). Sample searches were conducted to test the comprehensiveness of the results. A preliminary search of ASFA returned over 350 citations for "Delaware Bay" and 12 for "Don Maurer." No hits were found for "Delaware Bay benthos" and only four for *"Sabellaria vulgaris,"* though some 35 were found for "Cape Henlopen." This confirms the scarcity of such particular information and the variety of sources from which it must be recovered. In contrast, a broader search returned more than 3,000 citations for "dredge" or "dredging."

Well-known references were used to identify highly relevant works published before the citation date. The database searches, in effect, checked the thoroughness of the backward search in addition to identifying more recent, derivative works. These included publications in the primary literature resulting from a thesis or technical report. As with the hard-copy materials, I scanned the titles and abstracts to determine their relevance to this report. Unusual and curious references were sometimes uncovered. One of particular, though historical, interest was Bastian (1983). Remarkably, the first dredge in colonial America was employed in the Delaware River. In 1774, Arthur Donaldson used his newly invented clam dredge to clean out slips at Philadelphia's docks on the Delaware River.

Clearly, the literature on dredging, dredge spoil disposal, and their impacts is voluminous and is treated at length in textbooks (e.g., Kester et al. 1983, Clark 1996). A synthesis is clearly beyond the scope and resources of this project. Likewise, the ready availability of computerized databases means that a broad, conventional annotated bibliography would be of little future use. The focus here will be to compile what is known about the impact of spoil disposal on those benthic communities and habitats overlooked in previous assessments and to address specific questions regarding local spoil disposal scenarios to the extent possible given the existing literature, local knowledge, and conventional wisdom. Studies from elsewhere (e.g., Van Dolah et al. 1979) will be consulted as appropriate. Notably, in preparing the original proposal, I discovered at least two of Maurer's reports (Maurer et al. 1974 and Maurer, Keck, et al. 1978) that seemed to be highly relevant, dealing with local benthos, spoil disposal, and overburden effects. Nevertheless, these sources were missing from the SEIS.

Results of the database searches are summarized further in Appendix 4. In addition, lists of general reference works and identification guides for local habitats and species are provided in Appendices 2 and 3, respectively. The most readable of the general references are probably Gray (1981), Levinton (1995), and Raffaelli and Hawkins (1996). For identifications and basic natural history, Gosner (1978), Ruppert and Fox (1988), and Lippson and Lippson (1997) are good starting points. Watling and Maurer's 1973 *Guide* consists of comprehensive keys to the local fauna, but it is increasingly out-of-date. Identifications should generally be checked with other sources such as Pollock (1998).

Issues to Be Addressed

Results of a preliminary literature search were used to frame several issues with regard to the impact of dredge spoil disposal in the shallow regions of the lower Delaware Estuary. Consequently, the following issues will be addressed in this report:

- the quality of existing information on the benthos throughout the bay, with consideration of both hard- and soft-bottom communities,
- the validity of the "no significant impact" inference from prior benthic sampling,
- the adequacy of the completed survey work for assessing the benthic communities,
- the predicted impacts on benthos in and near disposal/stockpiling areas,
- the likely long-term impacts and possible mitigation strategies,
- the recommendations for minimizing or mitigating any suggested impacts, and
- the identification of questions relevant to future, field-oriented research projects.

Each issue will be discussed under an appropriate heading below.

Summary of Existing Information

Prior to the SEIS, there were three major research efforts of relevance to current issues regarding benthic communities in Delaware Bay.

Maurer et al. Survey (1972–73) and Reports

Don Maurer and colleagues at the College of Marine Studies of the University of Delaware conducted the first quantitative, baywide survey of benthic invertebrates. In each of two consecutive summers (1972–73), more than 100 stations were sampled with a 0.1-m^2 Peterson grab. Invertebrates were washed over a 1-mm sieve and preserved in 10% buffered formalin. Aliquots were taken from the grab samples for grain size analysis. Ancillary measurements of bottom salinity, dissolved oxygen, and temperature were also taken at each station.

The results of this survey are summarized in the Maurer, Watling, et al. (1978) *Marine Biology* paper. These results were variously presented in terms of statistical summary for the bay and by comparison with other estuaries. For example, the total numbers of species and individuals were positively correlated with increasing median sediment grain size in Table 1 of the paper. These relationships were found to be similar to those in other estuaries and bays throughout the world. The overall invertebrate abundance of 722/m^2 was, however, deemed low compared to other estuaries shown in Table 2 of the report. Possible explanations were discussed in terms of pollution, macroscopic algae, sediment transport, predation, and hydrography. The last paragraph of the relevant section (Maurer, Watling, et al. 1978, p. 70) acknowledged that these were untested speculations. An unstated assumption in this analysis was that low biomass reflects low secondary productivity (but see later publications by Maurer, Howe, and Leathem, 1981 and 1992).

Species composition was analyzed in two ways: by feeding functional group and by cluster analysis. The species composition was found to be similar to that of Chesapeake Bay, and the dominant species also occurred in estuaries throughout the Mid-Atlantic region. Deposit feeders were the dominant feeding group and were especially prominent along the western side of the bay, although this association was not clearly explained in terms of the grain size composition of the sediment. Suspension feeders were found on sandy and hard bottoms. None of the species discussed in detail were representative of hard bottoms.

Cluster analysis is a multivariate statistical technique designed to group samples or stations by similarity in species composition. Separate groupings were found for the 1972 and 1973 data and were plotted in Figures 4 and 5 of the paper. The only distinct epifaunal asemblage was so-called Assemblage 8, which occurred at scattered but well-defined localities throughout the bay and included the sandbuilder worm, *Sabellaria vulgaris*. In summary, Maurer, Watling, et al. (1978) concluded that the benthic invertebrates of Delaware Bay were found in a mosaic of assemblages of various sizes, some with distinct limits of distribution, others with less well-defined boundaries.

This *Marine Biology* paper represents only a summary of a very extensive sampling effort and considerable laboratory analysis. More detailed results were presented in technical reports, including

Maurer and Watling (1973a); Watling and Maurer (1973); Maurer (1974a and b); Maurer et al. (1974); Watling and Maurer (1976); Maurer, Keck, et al. (1978); Maurer, Watling, et al. (1978); and Kinner and Maurer (1978). As the dates suggest, the mid-1970s were a prolific period for Maurer and his colleagues. So many reports and publications were generated during this period that the use of the conventional author and year citation format leads to ambiguity. To avoid confusion, the title of the document will be included as needed.

Maurer's (1974a) *Biological Condition of the Deep-water Portion of the Lower Delaware Bay* is a brief summary of the ecology and ecological studies of the bay from the Chesapeake and Delaware Canal south to the bay mouth and its adjacent tidal, marsh, and coastal areas. While Maurer's own studies formed the basis for this discussion of benthic invertebrates, citations were made of pre-1970s work by researchers at Rutgers University. With regard to dredging and spoil disposal, several points were made. At this time, dredging for the canal was still under way, and disposal sites were mainly located north of the canal. Maintenance dredging for the Cape May-Lewes Ferry terminals had just been completed, and a summary of its impact was reported in Maurer et al. (1974). Although disruption of the benthic community occurred in the dredge and spoil areas, effects were localized to those areas. Further, Maurer noted that dredging projects had been conducted in many of Delaware's waterways, large and small, and that increased dredging associated with development of marinas had led to considerable environmental impact.

Maurer's (1974b) *Environmental Problems Associated with a Deepwater Port in the Delaware Bay Area* considered a broad array of impacts at each of four such facilities but mainly focused on the effect of selected oil-spill scenarios. Dredging impacts were only briefly and generally discussed within the context of construction and maintenance activities. Interestingly, in the "General Description—Sediment" section of this report, it was noted that serpulid worm colonies (therein termed "serpulid reefs") were well established on the southwestern slope of Old Bare Shoal. These were composed of the calcareous tubes of *Hydroides dianthus* (a key member of what are referred to below as the "coral beds"), and their distribution was sketched in the report's Figure 3. This figure is, in fact, one of the very few available indications of the location of the reefs. Impacts on several benthic communities were discussed individually, although the worm colonies were not discussed in any further detail.

Effects of Spoil Disposal on Benthic Communities near the Mouth of the Delaware Bay (Maurer et al. 1974) described impacts associated with dredging and spoil disposal related to the ferry terminal at Lewes in Breakwater Harbor. Benthic sampling before and after dredging and disposal found relatively low macrobenthic abundances, thus it was difficult to detect differences between natural and disturbed conditions. Any noted disruptions were localized to the dredge and disposal sites. The dominant benthic invertebrates sampled were mostly infauna of soft-sediment habitats. Down-slope movement of most of the spoil material was noted, but levels of suspended sediments in the disposal areas were not appreciably higher than natural levels. Experimental studies of the effects of simulated spoil disposal were described in Maurer, Keck, et al. (1978). This work resulted in subsequent journal publications by Maurer et al. (1981a, 1981b, 1982) and Maurer, Keck, et al. (1986).

The encyclopedic *Ecological Studies on Benthic and Planktonic Assemblages in Lower Delaware Bay*, edited by Watling and Maurer (1976), is a highly relevant, important work. It is a summary of intensive phytoplankton, zooplankton, and benthic studies conducted in 1974–75 in the oil lightering area of the lower bay off the Mispillion River. In addition to quantitative benthic grab sampling, extensive dredge haul samples were taken, and the effectiveness and utility of these two methods were evaluated. The most pertinent sections of this report are chapter 5, "Delaware Bay Benthic Invertebrate Assemblages" (Watling et al. 1976); chapter 6, "Seasonal Changes of Benthic Invertebrate Assemblages in the Lightering Area" (Leathem et al. 1976); and chapter 7, "Methodological Benthic Invertebrate Studies" (Kinner and Watling 1976).

The chapter by Watling et al. (1976), "Delaware Bay Benthic Invertebrate Assemblages," is a preprinting of the 1978 *Marine Biology* paper discussed above. In some cases, more detail is provided in the figures and tables, and thus this represents a valuable primary source.

Chapter 6, "Seasonal Changes of Benthic Invertebrate Assemblages in the Lightering Area" (Leathem et al. 1976), describes the results of seasonal sampling (five times, quarterly) at 10 stations in 1974–75. Two of the stations, Stations 8 and 9, were chosen to include a calcareous serpulid reef. Sampling was done with a 0.1-m^2 Peterson grab, and samples were washed over a 1.0-mm mesh sieve and preserved in 10% buffered formalin. At Stations 8 and 9, increases in the proportion of living *Hydroides dianthus* from August to February probably reflect recent colonization and active construction of the reef. However, by the following May, samples indicated that a set of blue mussels had overrun the area causing a major shift in the benthic community type. These results were later published as Maurer, Leathem, et al. (1979) and Maurer, Watling et al. (1979).

In chapter 7, "Methodological Benthic Invertebrate Studies," Kinner and Watling (1976) compared grab and dredge sampling in the bay. Dredge sampling is commonly employed but usually considered to be nonquantitative, yielding only presence/absence results. It is difficult to know the size of the area sampled, the sampling depth within the sediment, and the retention efficiency of organisms. This form of sampling is quite rigorous for the organisms, and small or soft-bodied organisms will not be collected (or be identifiable) to any certain degree. Four stations, including Station 9 (the calcareous serpulid reef mentioned above), and three dredges were used: a sled dredge with a flat blade, a modified oyster dredge, and a Menzies dredge with a modified blade. These dredges were depicted in the chapter as Figures 7-2, 7-3, and 7-4. Each of the dredges was equipped with a 1-mm Nitex cloth bag to retain specimens.

At all stations, the dredge sampled a larger number of species than the grab. At the reef stations, the grab sampled primarily a muddy sand, and the dominant species were infaunal polychaetes and clams, although epifaunal amphipods and crabs were also found (and believed to be associated with the reef structure). Dredge samples were distinctly different, dominated by the serpulid reef-former *Hydroides dianthus* and two amphipods.

Station 9 was located in an area containing large numbers of calcareous tubes constructed by *Hydroides dianthus,* not in a continuous structure, but as separate clumps spread over roughly 1 km^2. A very poorly sorted, very fine muddy sand (with traces of coarse sand) was found around, under, and in between the calcareous tubes. Station 9 was the only site in this comparative study where there was a significant difference in the order of abundance of species between grab and dredge samples. At this station, the dredge presented a view of the community structure considerably different from that obtained with the grab. These results appeared in the primary literature as Watling et al. (1978).

EMAP-E Virginian Province (1990s)

The Environmental Monitoring and Assessment Program (EMAP) is a nationwide initiative by the Environmental Protection Agency to provide information about the degree to which existing pollution control programs and policies protect the nation's natural resources. EMAP-Estuaries (EMAP-E) is the near-coastal effort focused on measuring status and changes in selected ecological indicators. Specific issues of interest include hypoxia, sediment contamination, coastal eutrophication, and habitat loss.

In 1990 and 1991, EMAP-E initiated a demonstration project in the estuaries of the Virginian Province, including coastal regions from Cape Cod south to the mouth of Chesapeake Bay. The 1991 sampling was conducted over a seven-week period in the summer, and two-thirds of the stations were so-called Base Sampling Sites (BSS), probability-based sites chosen according to the EMAP-E experimental design. Sampling locations were chosen randomly on a hexagonal grid within bays and rivers rather than selected by an investigator. Known technically as a stratified random design, this procedure ensures unbiased parameter estimates and permits calculation of confidence intervals about those estimates. Further, the design allows estimates of actual areas (or percent of total area) of specified ecological conditions. Such area estimates are generally not easily derived from traditional approaches to environmental monitoring and sampling where the intent is to gauge averages or integrated measures along a preselected gradient. The 1991 data represent only one year of a four-year cycle of sampling needed to fully characterize the region.

At the probability-based sites, samples were taken to allow habitat characterization and calculation of abiotic and biotic condition indicators. Habitat characterization included water depth, bottom water temperature, salinity, water density, water clarity from extinction coefficients, and grain size and silt-clay fraction of the bottom sediment.

Abiotic condition indicators included the conventional suite for water chemistry (inorganic nutrients, chlorophyll, and seston), bottom-water dissolved oxygen, sediment organic contaminants and metals, toxicity to amphipods, and the presence of marine debris (i.e., trash) in trawl samples. Finally, the biotic condition indicators used were a newly developed benthic index, fish trawl catch, incidence of external pathologies (growths, lumps, ulcers, and fin erosion), and selected sampling for contaminants in muscle tissue.

Sediment samples for analysis of benthic macroinvertebrates, silt-clay content, benthic chlorophyll, and sediment contaminants were collected using a 0.044-m^2 Young-modified Van Veen grab. Invertebrate samples were sieved in the field on a 0.5-mm mesh screen and preserved in 10% buffered formaldehyde stained with Rose Bengal. Species composition, abundance, and biomass were determined using methods outlined in the EMAP laboratory methods manual (Klemm et al. 1993) and updated by Frithsen et al. (1994). Macrobenthos were identified to the lowest practical taxonomic level and counted. Identified organisms were sorted into predetermined biomass groups, dried, and weighed. Bivalves and gastropods were acidified to remove inorganic shell material before weighing. In the Virginian Province, the sampling work was contracted to Versar, Incorporated of Columbia, MD.

Benthic assemblages were evaluated using abundance, biomass, diversity, and the EMAP benthic index. Diversity is measured by the number of species (i.e., species richness) at a site. The Shannon-Wiener diversity index comprises both species richness and evenness components (see Gray 1981). The EMAP benthic index integrates measures of species richness, species composition, and biomass/abundance ratio into a single value that distinguishes between sites of good and poor ecological condition (Schimmel et al. 1994). A value of zero or less denotes a degraded site at which the structure of the benthic community is poor, and the number of species, the abundance of selected indicator species, and the mean biomass are small.

Since 1997, EMAP-E activities relevant to Delaware Bay have been under the umbrella of the Mid-Atlantic Integrated Assessment (MAIA). Initially a joint effort of the EPA's Region 3 and EMAP, MAIA has resulted in additional partnerships with state and federal environmental programs.

Delaware Estuary Program/Environmental Consulting Services, Inc. (1992–93)

The Delaware Estuary Program sponsored a one-year survey of the benthic macroinvertebrates of the upper bay, in the Delaware River between the Chesapeake and Delaware Canal and Trenton, NJ (Environmental Consulting Services, Inc. 1993). Samples were collected seasonally from the spring of 1992 through the winter of 1993 in regions based on Delaware River Basin Commission (DRBC) water-quality zones. Samples were taken with a Ponar grab sampler (23 cm^2), one each for faunal and sediment analyses at each station. At some stations, additional weight was added to the grab to facilitate sample collection. Even with this measure, sampling was not successful at some stations. Faunal samples were preserved in the field in 10% buffered formalin stained with Rose Bengal to assist in sorting. Ancillary measurements at each station (surface and bottom) included temperature, dissolved oxygen, conductivity, and salinity. Water clarity was measured with a Secchi disk, and water depths and station locations were also recorded.

In the laboratory, faunal samples were washed over a 0.5-mm sieve and transferred to 40% isopropyl alcohol. Fauna were sorted by eye and with a dissecting microscope, separated, and counted. Identifications were made to the lowest practical taxonomic level. Wet weight measurements by taxon were also made for biomass estimates. Results were presented in terms of faunal density (number of individuals per square meter, in units of $\#/m^2$) and biomass (grams per square meter, g/m^2).

In addition, a Benthic Resources Assessment Technique (BRAT) analysis was conducted using the benthic data plus finfish stomach content data. Developed by the Army Corps of Engineers to quantitatively evaluate dredge and spoil sites, the analysis combines invertebrate prey availability with measured food value to important fish species. Samples taken for the benthic invertebrate survey were further analyzed by size class as determined by nested sieves, sorted and pooled by major taxonomic group, and weighed for biomass. This procedure yielded a matrix of invertebrate biomass by taxa and size group for each of the 12 study areas.

Fish were collected as part of another project sponsored in parallel by the Delaware Estuary Program. White perch, striped bass, and spot were collected by seine net or trawl and preserved in the field in 10% formalin after the body cavities were opened to ensure good preservation. In the laboratory, fish were sized and examined for stomach contents as an indication of actual fish diet. Measurements were made as described for the invertebrate samples. Biomass values were also converted to a percent of total stomach contents.

A trophic support value was calculated for each location for a given fish species and size class. This calculation was made by multiplying the dietary weight factor (from gut contents) by the invertebrate biomass for each taxon and size group, then summing to total the trophic contribution of that invertebrate group.

The macrobenthic community in the Delaware River between the C&D Canal and Trenton, NJ, is dominated by oligochaetes (sludge worms), chironomids (midge fly larvae), amphipods, isopods, polychaete worms, and clams, with each taxon dominated by a single species or genus. Relatively few taxa were seasonally and regionally dominant, indicative of the low-diversity community expected of freshwater-oligohaline transition regions. The oligochaetes and chironomids are considered pollution tolerant, surviving in environmentally stressful and low-oxygen conditions. As compared with historical data cited in the study, the composition of the community has changed in relative terms with increases in species considered less pollution tolerant and more oxygen sensitive. This may be suggestive of improved water quality in the study area since the mid-1970s, although future sampling would be required to determine if this change was fortuitous or indicative of a significant trend.

In this study, the benthic and gut-content data sets did not provide the desired taxonomic and size-class coverage designated in the BRAT analysis. Thus, the results were compromised by the sparse nature of the resulting matrices, although provisional conclusions were drawn. For example, using the most complete data subset for smaller white perch, it was concluded that shallow/intermediate substrata in two of the sampling zones were important summer feeding grounds and that amphipods were a very important food item.

Army Corps of Engineers Draft SEIS (1997)

The Philadelphia District of the Army Corps of Engineers has conducted studies pursuant to the Delaware River Main Channel Deepening Project. In Delaware Bay, dredged material from the initial construction would be used at four beneficial-use sites: wetland restorations at Egg Island Point, NJ, and Kelly Island, DE, and for stockpiling sand at Slaughter and Broadkill beaches. Since the wetland restoration studies fall outside the scope of this report, this discussion will focus on benthic studies at the proposed sand stockpiling sites in the bay itself. The following information is based on the January 1997 Supplemental Environmental Impact Statement (U.S. Army Corps of Engineers 1997, hereafter denoted "SEIS"). The most relevant portions of this document are sections 3, 8, and 9.

Eleven beneficial-use sites were initially investigated in 1993, and four were resampled in 1994, including the two sand stockpiling sites: L-5 (off Broadkill Beach) and LC-10 (off Pickering Beach). A twelfth site, MS-19B (off Slaughter Beach), was added in 1995 and evaluated by Versar, Inc. (Chaillou and Weisberg 1995). The LC-10 site was eliminated from consideration because it is an oyster lease area. Biological parameters measured included species composition, density of organisms, percent equilibrium taxa, biomass, numbers of large individuals, and commercially and/or recreationally important species (SEIS, sec. 3, p. 24). Sampling methods were incompletely described in the SEIS. Sites were evaluated on the basis of physical characteristics, presence of unique species (not collected elsewhere in the bay), presence of commercially or recreationally important species, and condition of the macrobenthic community (SEIS, sec. 8, p. 3). Physical characteristics considered for the sites included water depth, bottom sediment type, percent silt-clay fraction, percent organic matter, and surface and bottom water salinity, temperature, and dissolved oxygen. These results were summarized in Table 8-2 of the SEIS.

Of the 248 species found at either of the candidate sites or in the surrounding bay, 35 were unique to a particular site (SEIS, Table 8-3). Ten were unique to L-5 and six to MS-19B. It was concluded that none of the unique species were so important as to preclude use of the site. The stated reasons for this conclusion were as follows: Three of the species were epifaunal and not well sampled by the gear used. Five species were abundant at sites near the Atlantic Ocean. Eleven species were taxonomic relatives of others on the species list and represented uncertainties or inconsistencies in identification. Four species were in such low abundance (less than 2/m^2) as to be judged inconsequential. Of the four remaining species, none were considered rare in the bay in earlier studies (Watling and Maurer 1973). For background benthic data, the report relies extensively on the Maurer et al. and EMAP-E surveys.

Several commercial, recreational, or otherwise notable species were found at the sand stockpiling sites. Hard clams (northern quahog, *Mercenaria mercenaria*) were found in low abundance at MS-19B. The knobbed whelk *(Busycon carica),* the blue crab *(Callinectes sapidus),* and the horseshoe crab *(Limulus polyphemus)* were found at the nearby MS-19A site. Knobbed whelks and horseshoe crabs were also found at site L-5 (SEIS, Table 8-4).

Benthic community response measures were also used to characterize candidate sites. None of the sites were found to have significantly greater species richness or diversity than typical for the bay. Only two sites had benthic abundances judged to be higher than that typical in the bay. In each case, elevated abundances were due to a single, opportunistic species, and in any event, neither of these two sites has been selected for use. Site MS-19B had the highest percentage of equilibrium species, i.e., large, relatively long-lived species (which are slow to recolonize a site) often indicative of undisturbed or unstressed habitats. As may be expected, the MS-19A and B sites also had the highest percentages of large organisms (greater than 2 cm), notably the razor clam *(Ensis directus)* and the bloodworm *(Glycera americana).*

The relevant portion of the report (SEIS, sec. 8, p. 18) concludes with an assessment of potential impacts on the benthic communities of the candidate sites. Since no significant differences were found between candidate stockpile and background sites, it was concluded that no significant impact would occur due to the use of these sites for either wetland restoration or sand stockpiles. The potential effects associated with dredge material placement were then discussed in terms of published studies. Important factors include the depth of burial and the ability of the fauna to migrate vertically, larval recolonization from nearby areas, sediment contaminants and grain size characteristics, water depth, and wave action. Loss of the benthic community was expected to be a short-term adverse impact, while longer-term impacts would likely depend on how frequently the material would be used for beach nourishment projects. It was suggested that this use would affect only small portions of the stockpile at five- to ten-year intervals.

The report acknowledged that the benthic communities of some 225 acres of the PN-1A and LC-9 wetland restoration/shore protection sites (Egg Island Point and Kelly Island, respectively) would be eliminated and replaced by intertidal wetland habitat. These two sites were judged to have the poorest quality benthic communities among the candidates, low in diversity and high in abundance of opportunistic species. At the selected sand stockpile sites, L-5 and MS-19B, water depth would be decreased from 8 feet to 3 feet below mean low water, and this change was expected to significantly increase the effects of waves and tidal currents. The change to a sandy substratum would represent a greater change at the L-5 site than at the already-coarser MS-19B site. Since MS-19B had the highest quality benthic community, it was expected that this site would experience the greatest impact due to lower recovery potential. Although MS-19B has higher benthic community quality than the other sites evaluated, "there were no significant differences found between it and the background conditions of the Delaware Bay that would preclude its use" (SEIS, sec. 8, p. 20).

In summary, the January 1997 SEIS provided additional information and environmental analysis addressing concerns raised during the review of the 1992 feasibility report. In particular, benthic invertebrate sampling was used to assess habitat quality at selected sites in the bay. Since no significant differences were found between candidate stockpile and background sites, it was concluded that no significant impact would occur due to the use of these sites for sand stockpiles (SEIS, sec. 9, p. 5). Further, no unique benthic species were identified. While the stockpiling of dredged material was expected to result in the burial and destruction of the existing benthic community, recolonization and recovery were expected to be rapid. Long-term impacts, however, would be determined more by the nature and frequency of disturbance of these sites as part of future beach nourishment projects.

Subsequently, additional concerns have been raised over the impact of the dredged sand stockpiling in the lower Delaware Bay. As indicated in a notice for a public hearing in May 1998, the current plan is to place dredged material from the riverine portion of the project in existing or new upland disposal sites. In the bay portion, dredged material from the initial construction was to be used for wetland restoration at Egg Island Point, NJ, and Kelly Island, DE, and for stockpiling of sand for later beach nourishment work at Slaughter Beach and Broadkill Beach. In response to fishery and habitat-related concerns at the stockpiling sites, the Army Corps of Engineers' Philadelphia District has begun the design and cost-evaluation process for shifting placement of this dredged material to beneficial beach sites, such as Broadkill Beach.

In addition, the Philadelphia District has produced feasibility reports and impact statements for Broadkill Beach (Kropp 1994, Ruddy 1994) and Roosevelt Inlet-Lewes Beach (Ruddy 1995) nourishment projects. Ruddy (1995) described the benthic invertebrate assemblages of the shoreline along Roosevelt Inlet-Lewes Beach based on sampling by Maurer and Aprill (1979) at Cape Henlopen. The species list was that of a sandy-bottom habitat, supplemented with epifaunal species associated with the docks and pilings, including *Hydroides dianthus*. As cited in Ruddy (1995), the macrofauna of two potential borrow sites off Broadkill Beach were surveyed by Kropp (1994) in July 1994. Infaunal clams, worms, snails, and amphipods dominated both areas, and no exploitable, commercially important, or notable species were reported.

Hard-Bottom Habitats in Delaware Bay

The above studies have been methodologically limited to soft-bottom habitats. Although most of the bay's bottom is sandy or muddy, hard-bottom habitats, or "hard grounds," are known to enhance the diversity of marine life and to concentrate its biological productivity. Any picture of the benthos of the bay is incomplete without the hard grounds.

The bay's best-known community of this type is the oyster reef. Natural beds and planted grounds in both Delaware and New Jersey waters have supplied a major regional industry for over a century, although present harvests are but a fraction of peak levels (Tweed and Epifanio 1988). Importantly, the shelly bottom provides substratum for an impressive variety of invertebrates, among them mussels, "moss animals" (bryozoans), hydroids, and barnacles. Within the oyster reef mass itself, many other invertebrates, including polychaete worms, crabs, and oyster drills, may be found.

While oysters are largely absent from the lower reaches of the bay, hard-bottom habitats are represented there in the form of "worm rocks" and "coral beds." Far less published information is available on these communities. Anecdotally, they are known for their specialized invertebrate species and abundance of recreationally important fish. Because of their location with respect to the spoil disposal project and their economic value, these communities will be considered below.

Oyster Beds of the Upper Bay. The key, classical study of the oyster beds is Maurer and Watling (1973a and b). Between 1967 and 1971, 800 oyster dredge samples were collected from the bay beds and those of surrounding rivers. Variously sized dredges were used, with mouths ranging from 0.9 – 1.3 m wide, and these were towed for about one minute per sample. A gallon of dredge material was preserved in 70% isopropyl alcohol for later laboratory analysis. Samples were washed over a 0.25-mm mesh sieve. Overall, the diversity of species decreased with decreasing salinity up-bay, though the the type of substratum (firm or muddy) was of considerable importance in determining the nature of the community (epifaunal versus infaunal). The bay's oyster community was found to have strong similarities to that of Chesapeake Bay. The oyster beds not only provided a valuable economic resource, but also formed the basis for a diverse estuarine benthic community.

Commercially important oyster lease beds are found near the wetland restoration sites at Egg Island Point and Kelly Island, and resource agencies have expressed concern for the beds in light of project activities or unforeseen events (SEIS, sec. 9, p. 9). Two hydrodynamic sediment transport modeling studies were undertaken to evaluate these concerns. The Corps of Engineers acknowledged the calculated potential for sand burial and/or siltation but concluded that there would be adverse impacts on oyster beds only under the most extreme model conditions or in the case of catastrophic failure of the containment structures.

A similar modeling analysis was conducted for the sand stockpiling sites in the lower bay. At both sites, stockpiles are expected to migrate slowly onshore (over years to decades), though this motion could be overwhelmed by transport from a single storm event. There will be appreciable longshore transport of sand to the northwest. However, since there are no oyster beds at stockpile sites, it was concluded that there would be no impacts aside from those on other benthic resources as considered in section 8 of the SEIS.

Although not restricted to oyster shells, two polychaete worms, *Sabellaria vulgaris* and *Hydroides dianthus,* are commonly found in oyster communities (Maurer and Watling 1973a and b). In some cases, *S. vulgaris* occurs so densely that it creates its own hard bottom between the oyster beds, and it has been considered a pest by local oystermen. In the lower bay, both these species form distinct types of hard-bottom communities that are well recognized, if far less thoroughly studied, than oyster reefs. Possible project impacts on them are not considered in the SEIS, either in terms of spoil emplacement or effect of spoil transport.

Worm Rocks along the Lower Bay Shoreline. Of particular interest is the effect of dredge spoil disposal on the "worm rocks." This is the local name for reef-like aggregations of well-cemented tubes of the sandbuilder worm, *Sabellaria vulgaris*, also known as the reefworm. Colonies, from football-sized to many meters across, are commonly found on hard substrata, and smaller aggregations can be found on oyster shell, rocks, and even other worm tubes and hermit crab shells (Karlson and Shenk 1983). Photographs of the reefs and tubes may be found in Wells (1970). Along the East Coast, this species is distributed from Cape Cod south to Georgia waters, from the lower intertidal to subtidal depths, and in estuaries to salinities as low as 15‰ (Gosner 1978, Lippson and Lippson 1997). In Delaware Bay, the worm rocks have been found widely along the lower bay's Delaware coast, from Cape Henlopen to the mouth of the Mispillion River (Curtis 1973, 1975, 1978; Pembroke 1978) to the Murderkill River (Watling and Maurer 1973a and b). As mentioned above, *S. vulgaris* is often found in association with oyster beds (Maurer and Watling 1973a and b, Hidu 1978).

Worm rocks are rock-like masses of sand grains cemented together to form the tubes of the sandbuilder worm. While existing as massive reefs low in the intertidal zone in the early 1970s, a survey from Broadkill Beach to South Bowers in the summer of 1998 uncovered only one reef rock with only two live specimens. This species is, however, quite abundant in the area and is commonly found on the backs of horseshoe crabs. Reef-forming activities are apparently restricted to Delaware Bay populations. Today's lack of intertidal reef masses may be due to ongoing beach erosion, last winter's severe storms, or other causes.

Aside from this basic natural history, there is relatively little published information on this species, its trophic relationships, or the significance of worm rocks as structure and habitat for other invertebrates and finfish. Locally, there seems to be little other than anecdotal observations and few, if any, quantitative data on the recent distribution of this species. Like other members of its polychaete family (Sabellariidae), the sandbuilder worm is a particle feeder, dependent upon and influenced by seston and resuspended sediment for food particles as well as tube material. The fact that beds are found on hard bottoms—presumably erosional (as opposed to depositional) environments—suggests that spoil disposal will be catastrophic to the beds. Scouring by sediment transport or sand mining activities may well prevent reestablishment of the beds. The magnitude of any effects will be a function of the distance from the beds to the stockpiles, wind and wave fetch, and tidal current patterns. In addition, since reefs provide structure on otherwise flat sandy bottoms, it is likely that the worm rocks form valuable microhabitat for other benthos and bottom-dwelling fish species.

Coral Beds in Lower Bay Sloughs and Shoals. Certain subtidal hard bottoms found along the sloughs and shoals of the lower bay are popularly known as "coral beds." In response to recent public concern, a reconnaissance of these habitats was undertaken in the summer of 1998. Samples taken in the Broadkill Slough, off Fowler Beach, showed a sandy bottom with orange clumps or nodules of worm tubes. Thus the coral beds are not coral reefs, nor do corals produce their dominant structure.

Closer examination revealed that the nodules are formed by a consortium of three animals: two species of worms and an encrusting bryozoan (also known as a "moss animal"). The nodules consist of the limy white, calcareous tubes made by the featherduster worm (or limy tube worm), *Hydroides dianthus*, and the darker, sand-grain tubes built by the sandbuilder worm, *Sabellaria vulgaris*. Covering these tubes is the orange encrusting bryozoan, *Schizoporella unicornis*. A true coral (the star coral), rubbery bryozoans, and redbeard sponges are also found in the area. The more resistant white worm tubes, bryozoans, and sponges are commonly found on shore by beachcombers at the tideline.

While not identical to the serpulid reefs described above by Leathem et al. (1976), Kinner and Watling (1976), Haines (1978), and Haines and Maurer (1980a and b), these two reef communities are clearly related. It is unknown whether any such differences reflect community changes over time, spatial variation, or the influence of other biological or physical factors.

As is the case with the worm rocks, species composing the coral beds and their associates are not considered in the SEIS impact assessment. Conventional benthic sampling grabs were used in both historical (e.g., Watling and Maurer 1976; Maurer, Watling, et al. 1978; and Maurer and Aprill 1979) and more recent benthic surveys (EMAP-E and the SEIS). Hence, it is not surprising that the typical hard-bottom species are absent from species lists and merit no consideration in the assessment of potential impacts.

Summary of Benthic Studies

Although comprehensive in a geographical sense, the Maurer et al. and EMAP-E surveys represent essentially only two points in time, namely the early 1970s and the early to mid-1990s. These studies were undertaken for different purposes: one as a study of the benthos of the bay itself and one as part of a large, nationwide project of environmental quality assessment. Because of their differing purposes, sampling designs, and methods of summary analysis, the derived reports are at times of limited use for novel purposes, such as impact assessment for a particular project.

To employ existing data, it is preferable to access the raw data in the form of original species-by-station lists. It appears that such data exists in archived technical reports and more recently in electronic form. Nevertheless, substantial expert interpretation is required before it reaches the primary literature. Widely accessible, published analyses are relatively rare and contain only summaries of the data. One example is that of Maurer, Watling, et al. (1978), based on their 1972–73 survey work discussed above. Another published analysis is that of EMAP-E data by Billheimer et al. (1997). Despite its title, "Natural Variability of Benthic Species Composition in the Delaware Bay," this paper is less an analysis of the benthos of the bay than a presentation of a mathematical model for monitoring data. While the authors present some intriguing plots of faunal distributions, the statistical methods are highly sophisticated, if not arcane. The only conclusion of ecological relevance is that the distribution of benthos in the bay depends significantly (and rather unsurprisingly) on salinity.

It is clear from the Corp of Engineers' SEIS as well as the literature search that the Maurer et al. and EMAP studies are the most pertinent to dredging impacts. The Delaware Estuary Program/ Environmental Consulting Services, Inc. study was conducted in the oligohaline, riverine section of the bay. In terms of both geography and benthic community assemblage, it has the least relevance to the current channel deepening plans and dredge spoil disposal impacts considered here.

As dictated by funding opportunities and current scientific questions in marine ecology, recent studies are focused on one site, species, or ecological process. None are comprehensive, and even taken together, they do not yield a body of information sufficient to address many resource management and habitat utilization questions. They do, however, reflect the biological diversity, trophic relationships, and important ecological processes operative in the bay.

Validity of the "No Significant Impact" Conclusion

The SEIS concludes that "there were no significant differences found between it [site MS-19B] and the background conditions of the Delaware Bay that would preclude its use" (SEIS, sec. 8, p. 20). Because no significant differences were found, it was assumed no significant impact would occur due to the use of any of these sites. This conclusion can be criticized on the following eight grounds:

1. The conclusions are couched in general terms such as "recolonized quickly," "minimized effects," and "did not vary appreciably." The use of such soft terms makes it difficult to understand precisely what is meant by the "no impact" assessment. The data in hand and literature reports could be used to answer certain relevant questions more precisely. How rapidly will the site be recolonized and by what sequence of species? What is the magnitude of the expected effect on benthic

abundances and biomass? And how much of a difference is judged to be appreciable?

2. The use of the term "significant effect" is particularly confusing. According to the dictionary, significance refers to meaning, import, or consequence. When used in the context of a quantitative and numerical analysis, the term is usually meant in its statistical sense. In this context, it is a probability statement based on well-established statistical methods. Although no hypotheses are tested explicitly in the SEIS, and thus the strict sense of the term may not apply, its use there does connote an authority beyond that provided by the simple, relative analysis. Lacking a rigorous statistical analysis, significance implies some subjective determination of meaning, import, or consequence. However, the basis for that determination is not described in the SEIS.

3. Whether or not the candidate sites are significantly different from others in the bay has no relevance whatsoever to the impact of a given project. The actual assessment of site differences, using either the dictionary or more restrictive statistical definition of significance, is completely independent of any proposed project. Determination of difference or lack thereof only indicates whether unique or extraordinary sites could possibly be affected, assuming that the project will result in major habitat alterations.

4. The engineering details of the spoil disposal project are described only in terms of the change in water depth resulting from deposition of a meter or more of sandy material. The existing benthic community will be buried and destroyed, and a new community will recolonize the deposited material. While this is undoubtedly the course of events, the rate and species composition of the pioneer community at the site will be seasonally dependent and alter the anticipated months-to-years time scale of recovery. Other important factors to consider are the grain size (median and sorting), organic matter content, and reducing (anoxic and sulfidic) state of the sediments (Weston 1990). In the absence of this information, it is difficult to predict the successional sequence of the benthic community or whether the new community will resemble the preexisting one.

5. The change in water depth due to emplacement of dredged material may be up to 5 feet, and the possible effects of this change are discussed in the SEIS (section 8, page 19). The arguments presented are convoluted but assert that when the resulting bottom is deeper than 6 feet (2 m), there will be little change in the benthic community. Allowance is made that changes may occur in communities shallower than 2 m, although the expected changes are not described. An arbitrary 2-m cutoff for effects is far too simplistic. Tidal currents and storm waves easily reach deeper bottoms and transport or resuspend bottom sediment. This physical forcing is superimposed on a bottom that is characterized by ridges and swales of a meter or more in amplitude.

6. By the SEIS analysis, site MS-19B is judged the best benthic community, yet even this assertion does not preclude its selection for a disposal site. Presumably, there would be no impact of importance at any of the possible sites. This is essentially a worst-case analysis, concluding that the loss of the benthic community at any site (including the best) would result in loss of no unusual or irreplaceable resources or habitat. A detailed comparison of other sites is thus rendered moot.

7. Effects of spoil emplacement on the benthic community are asserted to be temporary and localized based on several cited studies. This inference represents an extrapolation and generalization from studies of other projects and the response of different benthic communities (e.g., Maurer et al. 1974, Van Dolah et al. 1979, Maurer et al. 1981a and b, Maurer et al. 1982, Maurer et al. 1985, and Maurer et al. 1986). The degree to which these situations and results are applicable is not adequately justified. Even where spoil effects have been investigated locally (Maurer et al. 1974), the results are of uncertain application because of obvious differences in benthic community (typical of finer-grained, silty sediments) and hydrodynamic situation (deeper, tidally forced).

8. Impact assessment is focused narrowly on the spoil disposal sites without consideration of

how material dispersed by tidal currents and storm action might affect nearby communities. Also, if a site is to be used for stockpiling, there will be at least two subsequent disturbances to benthic communities: one in mining and recovering the material and one in the final emplacement, for example, for beach nourishment. In effect, over the lifetime of the project, roughly three times the original bottom area will be disturbed.

Adequacy of Existing Survey Data

The surveys described above represent the most thorough studies of the benthic communities of the Delaware Bay that were identified in the literature search. Further, they represent the database from which the conclusions of the SEIS are drawn. Baywide surveys are of such a scale that only multiple principal investigators with considerable external financial support can undertake them. It is telling that the last survey conducted through an academic institution was 25 years ago. Such survey work now lies outside the mainstream of benthic ecology as a discipline. While sufficient resources can be garnered for investigations at particular sites, broad surveys can only be supported by agencies with resources like those of state or federal governments.

The type of sampling gear used is critical to the results of a benthic survey. A grab sampler, with curved jaws that close to retrieve a bite of the bottom, is most commonly used from small vessels. Grabs are generally easy to handle and work reliably. However, the sample is usually disturbed and mixed by the closing of the jaws. In addition, the very top layers or first few millimeters of the bed are blown away by a bow wave as the grab reaches the bottom and are thus ineffectively sampled. This latter effect is less important for large infauna than for small meiofauna. Meiofauna are usually not part of a benthic assessment survey for sorting and taxonomic reasons as well as sampling efficiency. Allowing for these limitations, grabs work well in muddy and sandy sediments.

Gravel, rocks, tree branches, or other material that might lodge in the jaws of a grab sampler will allow any sample to wash out upon retrieval. Grab sampling would be particularly biased and ineffective on hard or rocky bottoms. Even in sandy environments, large and deep-burrowing fauna will not be sampled due to the limited depth of the grab's bite. A box corer sampler overcomes many of the limitations of a grab but at a much greater cost for the device and for the large vessel required for fieldwork. Bottom trawls or dredges are used on hard bottoms with considerable success, but their samples are usually not considered to be quantitative.

Benthic animals are separated from the sediment by sieving on brass mesh screens of known size: sediment is washed through, while organisms are retained on the sieve. Sieving may be done either in the field, prior to fixation with formalin, or in the lab, or both times. Samples are routinely re-sieved to wash irritating fixatives from the sample. The choice of mesh size is important, and typically either 1-mm or 0.5-mm mesh is chosen, with the latter value being more common today. These correspond to the operational size cutoff for benthic macrofauna, but they also represent a choice to maximize the efficiency of sample processing and sorting. Organisms retained on the sieve are washed with tap water to remove salt and fixative; sorted, identified, and counted by eye or preferably under a dissecting microscope; and preserved in alcohol.

A smaller sieve mesh size obviously retains smaller animals, so the numerical results depend somewhat on the choice of mesh size. The best approach is to standardize on a size, say 0.5-mm mesh, as has been done in the EMAP methods. In fact, the laboratory methods prescribed for EMAP benthic sample processing are efficient, reliable, and laudable.

Identification to species is not always possible or practical for all animals. Certain groups are conventionally lumped together at the genus, family, or order taxonomic levels. Some species are readily recognized or keyed out; others require taxonomic specialists to identify with certainty. If identifications are reliable for those animals with the greatest abundance (or those of some other importance), the overall analysis is in no way compromised. One caveat here, especially when comparing studies conducted over some span of time, is that names of organisms may be changed by taxonomic experts and authorities. When questions of identification or nomenclature arise, the best recourse is to contact an expert and recognized authority in that particular taxon for an opinion.

Once data are tabulated, usually as numbers of a species by site (or sample), some sort of summary analysis is conducted. Results are often expressed as average abundance per square meter, total abundance (summed for all species), or number of species. Indices expressing species diversity by dominance or evenness of abundance are also often used. Modern analyses allow adjustment for different samplers and sampled areas to a common basis (e.g., rarefaction curves, Gray 1997). If biomass measurements are made (by weighing specimens or other size determinations), certain more recent biomass-diversity indices may be used to infer environmental or habitat quality from benthic samples (e.g., the B-IBI, Weisberg et al. 1997). Sites can then be compared amongst one another, with other survey results, or with data from other systems. Alternatively, multivariate statistical methods such as cluster analyses are also used to ascertain groupings or similarities among sites. While summaries, indices, and statistical analyses are useful analytical tools, reference must often be made to the raw abundance numbers. For this reason (and because of identification uncertainties and changes), it is crucial to retain the raw data tables indefinitely. Such raw tabulations are not published in the primary literature, so they are often archived in technical reports. Of course, abundance matrices are most conveniently distributed electronically as text or spreadsheet files.

Another problematic bias is present if sampling is restricted only to the area directly impacted by the spoil project. Unless it can be guaranteed that there will be no effects outside the limited project area, assessment of nearby communities is pertinent. Given the mosaic of bottom communities found in the bay and the potential for sharp boundaries between communities, sampling around as well as within the project area is necessary as a minimal effort.

The most notorious issue with respect to benthic sampling in the bay is that of sieve mesh size. While important, this matter is for present purposes less critical than bottom-type biases inherent in the use of a grab sampler, both in terms of sample collection and choice of potential use site. The soft-bottom sampling methods routinely employed are fully adequate for soft-bottom habitats. Delaware Bay is, however, a mosaic of soft- and hard-bottom communities. The adequacy of the existing survey work for benthic community assessment hinges on this point.

Impacts and Mitigation

It is reasonable to assume that emplacement of dredge spoils will smother the benthic community and bury it, resulting in the death of all individuals and a defaunation of the bottom at the site. This prediction should hold regardless of the engineering details, existing bottom type or community, or type of disposal material.

Predicted Impacts of Spoil Disposal

Recolonization of the site by benthic invertebrates will quickly proceed. Opportunistic species will likely be the first to populate the site, often as a very high abundance of small individuals tolerant of disturbed or anoxic sediments. Depending on the seasonality of recruitment of other species and the bottom type and hydrodynamic regime, other species will follow in succession. In the absence of further disturbance or other alterations in the environment, this will ultimately result in the establishment of a stable community composed of large, long-lived, so-called equilibrium species. There is a large body of literature on succession in benthic communities, and this process has been extensively studied over many decades. Succession occurs as a result of many natural events and man-made insults, including oil spills, sewage outfalls, ice scour, and bottom trawling as well as spoil disposal. A review of this literature is beyond the scope of this report, but citations can be found in the general references listed in Appendix 2 (see especially Gray 1981, Levinton 1995, and Raffaelli and Hawkins 1996).

At sites where there is regular sediment movement or resuspension of fine material, the region for some distance around the spoil emplacement is likely to be affected. Depth of burial by sediment should be considerably less at surrounding sites than in the emplacement area. Impacts will be less catastrophic and mostly sub-lethal, with loss only of infauna with limited burrowing ability and sessile, hard-bottom fauna. If the region is exposed and experiences frequent sediment movement, then the fauna may well be adapted to sediment deposition and erosion and experience little if any change. Fine material winnowed from spoils or resuspended should only be detrimental in high concentrations or where it forms a thick or fluid mud layer on the bottom. Suspension-feeding infauna and epifauna will experience difficulty in feeding and ventilation due to high concentrations of fine particles. Short-term effects are probably minimal, whereas longer exposure to high concentrations would interfere with feeding, respiration, and growth.

Given funding limitations and expediency, impact studies tend to be parochial in sampling and analysis. Benthic communities outside the project area may not have been sampled, yet may differ considerably from those found at the site itself due to patchiness. Thus, impacts on areas beyond the spoil site are much less certain, both in terms of whether they will occur at all and what types of impacts to expect. The project should ideally be considered in the context of a mosaic-like benthic environment and the long-term movement of the spoil materials.

The direct impact of spoil emplacement is loss of the existing (and possibly surrounding) benthic community and is clearly one of several important questions in the overall evaluation of a project. The other key questions are what type of benthic community will replace the original one, and how that community will respond to the disturbance of sand mining activities over the longer term.

Long-Term Impacts and Mitigation

While short-term effects of spoil emplacement on benthic communities are clearly catastrophic, recolonization of the defaunated area will permit long-term reestablishment of a benthic community, although perhaps one differing from that prior to spoil disposal. The time to reach a new, stable community is likely to be months to years, depending on the seasonal recruitment of many species. Lateral migration of fauna from nearby, undisturbed areas by crawling, burrowing, swimming, or transport by tidal currents or wave action will facilitate recruitment in defaunated areas and aid in reestablishing communities typical of that in the area.

The hydrodynamic regime and emplaced sediment characteristics are both important determinants of the new benthic community type. Flow and susceptibility to wave action will be primarily determined by water depth. Deep areas made considerably shallower by spoil emplacement would be expected to show an increase in physical disturbance, a coarsening of sediment, and an enhancement of benthic fauna tolerant of exposed, high-flow environments. Fine-grained sediments rich in organic material will be initially colonized by opportunistic species such as capitellid polychaetes. Coarse sands will be less attractive to smaller infauna but may prove favorable to establishing beds of suspension feeding bivalves. The successional trajectory and long-term development of the benthic communities are so dependent on these factors that little predictive analysis can be done without their consideration.

Mining of the stockpile material for beach nourishment represents another disturbance event, once again causing loss of the benthic community. Without specifics on the frequency of mining disturbance and its magnitude (e.g., depth of removal), it is reasonable to predict loss of the community and recolonization, again over months and years, depending on the factors described above. If mining occurs regularly at a site, there will be a regular defaunation and recolonization, a periodic resetting of benthic succession. Depending on the frequency, area, and repetition of disturbance, the project area may develop a patchwork of benthic communities in various stages of benthic succession.

From one point of view, sediment movement, defaunation, and recolonization are naturally occurring processes to which benthic organisms are adapted. Even a large spoil disposal project may not represent an unprecedented event in a geologically dynamic environment like the bay when seen over a long enough period of time. From a baywide perspective, disposal effects are localized, and it is difficult to imagine that any could have a major effect on ecosystem-level processes. However, this does not preclude substantial effects on particular resources or habitats, depending on the location, scale, and timing of the project.

Mitigation Recommendations

The best sites for spoil emplacement would be those resulting in minimal changes in sediment grain size, water depth, and benthic community composition. Assuming that some alteration is unavoidable, smaller affected areas would more quickly recover and be more like surrounding benthic communities. Since spoils are unconsolidated soft sediments, disposal should be in areas away from, and with little or no expected transport to, hard grounds.

To minimize the total area affected over many years or projects, disposal sites should be reused to the extent possible. Since many state and federal agencies are involved in these projects, coordination of site usage would be necessary. Dedicating or "zoning" regions of the bottom for long-term usage could avoid many permitting issues, scientific and political, with each project. Increased engineering costs for a given future project would be partially offset by cost savings because a thorough benthic resource assessment would be unnecessary. Some regions of the bay are already reserved for a given purpose (e.g., oyster grounds) and fall under separate management oversight. Other hard-bottom habitats may likewise merit inclusion in a "benthic reserve" system because of their unique species or valuable habitat characteristics.

Since the benthos of the bay consist of a mosaic of communities, hard grounds or other valuable or unique resources may be unavoidably affected by spoil disposal. Small habitats in the project area may be missed in the initial survey, or material lost or winnowed may be deposited on communities some distance outside the project itself. The extent to which hard-bottom communities can be reclaimed or established to mitigate loss is an important issue in this case. There is great potential in this approach because it is often employed in fisheries management, and the results of the efforts can be rapidly assessed. For example, oyster grounds are regularly seeded with shell material known as "cultch." Artificial reefs are usually designed to enhance fishing, but the establishment of an epifaunal benthic community is key to feeding the fish attracted to the structure. Many of the hard-ground animals are sessile epifauna with planktonic larvae. Assuming that adults are abundant elsewhere in the bay and producing larvae, all that would be required is to provide suitable hard substratum at the right time for settlement. Within weeks, sampling could quickly verify the reestablishment of a desirable epifaunal benthic community.

Relevant Research Questions

This white paper analysis has reviewed the literature on the bay's benthos, assessed its adequacy for spoil disposal project evaluation, reassessed possible impacts, and suggested mitigation strategies. Within these areas, several questions have arisen that could be addressed by field-oriented research projects.

The hard-bottom habitats of the bay need to be characterized in terms of their general distribution and species composition. With regard to the worm rocks and coral beds, the lack of hard information is in contrast to the abundance of anecdotes. Popular names mean little, since access to the primary literature and expertise on a given organism is through the scientific name. Actual specimens and reliable identification must be obtained as a preliminary step. Given the literature on the species of concern, and extrapolations based on taxonomic affinities and functional groupings, valid predictions and interesting scientific research questions can be posed.

With specific reference to the worm rocks and coral beds, important questions include the susceptibility of the worm colonies to burial during construction activities and by sand (or fine sediment "clouds") subsequently redistributed by storm waves and tidal action. Changes in water-column depth (bed depth below mean low water), tidal exposure, and the effects of trophic relationships (e.g., water column versus sediment primary production) could result in benthic community shifts. The seasonality of recruitment and any special sediment or habitat requirements will undoubtedly bear on the reestablishment of the beds, subsequent reef growth rates, and typical lifetimes. Benthic and finfish species are associated with the beds, and the potential of the use of coral beds as habitat for valuable fishery species should be assessed.

It is highly desirable that all the hard-ground communities of the bay (not just those of economic interest) be mapped efficiently. Perhaps side-scan sonar or other acoustic techniques (e.g., Pinn and Robertson 1998) can accomplish this remotely. "Ground-truthing" by direct sampling would be necessary but extremely useful. Representative monitoring stations could be occupied. Hard-bottom reserves could be identified and might prove a useful management tool. This would specifically address the issue of the presence of worm rocks and/or coral beds within (or in proximity to) sand disposal and storage sites.

Benthic sample collection and processing methodology has been standardized by the EMAP-E project. Given that this project is the only current major survey effort, a critical analysis should be made of the limitations of the data with respect to hard-bottom communities. If possible, standardizing sampling gear and sample processing for hard-bottom habitats should also be attempted.

Given access to the raw data of the Maurer et al. and EMAP-E surveys, it may prove useful to synthesize these data sets and to resolve any inconsistencies in identification or nomenclatural changes over the intervening 25 years. Despite their differing purposes and deficiencies, they each represent valuable "snapshots" of the bay's benthic communities, time points in a future status and trends analysis. Also, this would provide reliable species lists and up-to-date identification references and keys for future investigators. It would provide an opportunity to reopen issues of abundance, species diversity, and productivity raised by Maurer's study. Introduced species and biodiversity are both topics of great current academic interest, and a 25-year, combined data set would be an invaluable resource.

Storms and tidal currents are natural agents of sediment movement, and benthic animals are well adapted to living in a dynamic environment. It is quite reasonable to hypothesize that certain species or functional groups, or even certain community assemblages, will be adapted to frequent, natural sediment movement, burial, and erosion (Brenchley 1981). For example, large and deep-dwelling deposit feeders may, by virtue of their size and burrowing activity, be tolerant of deposition and erosion. Because nor'easters are the most frequent and predictable storms affecting the bay, winter populations may be more tolerant of (i.e., less susceptible to) disturbances than summer populations of growing and recruiting individuals (Peters and Pilson 1985, Pullen and Yancey 1979). If impact tolerances can be measured and the range of susceptibility identified, this information may prove useful in spoil disposal project design. Possibilities in terms of execution and mitigation strategies suggested by this work include seasonal phasing of projects; disposal of spoils in thinner, separate layers or capping spoils with a preferred bottom type; and better prediction of far-field effects. A better value judgement could then be made even in the planning stages, since we could predict the response of those species of unique and particular value to us. There is also the potential for the "adaptive" management of projects based on rapid monitoring of site properties such as layer thickness and depth to anoxia within the bed. Given this number of unknowns, a full program of laboratory and field experiments can be proposed.

Conclusions

Library catalog and on-line searches uncovered numerous studies of the ecology of Delaware Bay. Much of the work focuses on bay plankton (e.g., blue crab larvae) or finfish. Benthic studies have focused either on certain sites (e.g., Cape Henlopen) or fauna (e.g., oysters and horseshoe crabs) of particular interest. Because of their broad geographic coverage and, in particular, their use in support of impact assessments, the work of Maurer et al. in the early 1970s and the more recent sampling as part of the EMAP-E Virginian Province program were both selected for detailed consideration. Since these surveys were limited by sampling gear to soft-bottom habitats, a separate discussion of important hard-bottom habitats was presented.

Based on this summary of existing information on the bay's benthic communities, additional questions relevant to the proposed dredging of the bay's main channel were addressed. The conclusion of "no significant impact" presented in the U.S. Army Corps of Engineers' January 1997 Supplemental Environmental Impact Statement (SEIS) was criticized on eight separate points. While the arguments presented in the SEIS are not without merit, they miss the point that there are hard-bottom communities located in the general area of proposed sand stockpiling sites. These were not adequately sampled in the field and thus are not considered in the report analysis. A critical analysis of the existing survey data was also made. Since sampling devices used in conventional benthic sampling work poorly on hard bottoms, there is an intrinsic gear bias in the surveys. This represents the greatest limitation inherent in the existing data sets.

It is reasonable to assume that emplacement of dredge spoils will smother the benthic community and bury it, resulting in the death of all individuals and a defaunation of the bottom at the site. This prediction should hold regardless of the engineering details, existing bottom type or community, or type of disposal material. While short-term effects of spoil emplacement on benthic communities are clearly catastrophic, recolonization of the defaunated area will permit long-term reestablishment of a benthic community, although perhaps different from that prior to spoil disposal. The time to reach a new, stable community is likely to be months to years, depending on the seasonal recruitment of many species. Lateral migration of fauna from nearby undisturbed areas by crawling, burrowing, swimming, or transport by tidal currents or wave action will facilitate recruitment in defaunated areas and aid in reestablishing communities typical of that in the area. The hydrodynamic regime and emplaced sediment characteristics are both important determinants of the new and eventual benthic community type.

The best sites for spoil emplacement would be those resulting in minimal changes in sediment grain size, water depth, and benthic community composition. Assuming that some alteration is unavoidable, smaller affected areas would more quickly recover and be more like surrounding benthic communities. Since spoils are unconsolidated soft sediments, disposal should be in areas away from, and with little or no expected transport to, hard grounds. To minimize the total area affected over many years or projects, disposal sites should be reused to the extent possible.

The preceding white paper analysis has reviewed the literature on the bay's benthos, assessed its adequacy for spoil disposal project evaluation, reassessed possible impacts, and suggested mitigation strategies. Within these areas, several questions have arisen that could be addressed by field-oriented research projects. The hard-bottom habitats of the bay need to be characterized in terms of their general distribution and species composition. With specific reference to the reef-like conglomerations of worm tubes known as "worm rocks" and "coral beds" and their associated fauna, important questions include the susceptibility of the worm colonies to burial during construction activities and by sand (or fine sediment "clouds") subsequently redistributed by storm waves and tidal action. All the hardground communities of the bay, not just those of economic interest, should be mapped efficiently. Given access to the raw data of the Maurer et al. and EMAP-E surveys, it may be useful to synthesize these data sets and resolve any inconsistencies in species identification or nomenclature over the 25-year interval between the surveys. Storms and tidal currents are natural agents of sediment movement, and benthic animals are well adapted to living in a dynamic environment. It is reasonable to hypothesize that certain species or functional groups, or even certain community assemblages, will accommodate frequent, natural sediment movement, burial, and erosion. Laboratory and field experiments, from modest water-tunnel flume studies to large-scale field manipulations, could be used to study these hypotheses.

Appendix 1:
Glossary of Benthic Terminology

The following are terms found in the reports reviewed for this project in addition to being used in this document. Definitions given are those generally used within the context of benthic survey or impact assessment studies. Further information may be found in the references listed in Appendix 2.

Aliquot — a division of a sample or a subsample for convenience of laboratory processing, sorting, or enumeration.

Amphipod — a type of crustacean characterized by a laterally compressed body; includes many marine, freshwater, and semi-terrestrial species, sometimes called "beach hoppers," "sand fleas," or "scuds."

Bay, the — Delaware Bay.

Biomass — measure of the weight of organisms in a unit area, usually in one square meter; also called "standing crop."

Bivalve — an animal with a shell composed of two halves, such as a clam.

Bryozoan — sessile and colonial, composed of tiny individuals known as zooids, forming chitinous, gelatinous, or calcareous encrustings on shells, rocks, and other hard substrata; also erect, vine-like, or bushy.

Chironomid — a family of flies (in the insect Order Diptera); these larvae are common infauna in fresh or oligohaline waters.

Density — number of organisms per unit area of the bottom, usually per square meter. For macrobenthos, values range up to tens of thousands per square meter. Also termed *abundance of organisms.*

Diversity — number of species found in a sample or at a site; equivalent to *species richness.*

Epifauna — fauna living on or near the surface of a firm substratum or the sediment. More generally, *epibenthos.*

Errant — motile and actively moving animals.

Eutrophication — state of a body of water or benthic habitat characterized by excess biological productivity, often resulting from nutrient enrichment, and in the extreme resulting in noxious algal blooms and other undesirable plant and animal species.

Gastropod — a snail.

Grain size, sediment — diameter of individual grains in a loose (unconsolidated) sediment. Sand grains range in size from less than 2 mm to greater than 0.062 mm (62 μm), silt from less than 0.062 mm to 0.004 mm (62–4 μm), and clay from less than 0.004 mm to 0.0002 mm (4–0.2 μm). For sands, size is usually determined by shaking sediment through nested, size-graded mesh sieves and weighing the retained fractions. *Median grain size* is the most often quoted measurement of size: half of the sediment (by weight) is larger than this, half smaller.

Equilibrium species — organisms usually characterized by large size, slow growth, long life spans, and low fecundity (few offspring), with stable population levels at or near the carrying capacity of the environment; also termed *K-selected species. See* **opportunistic species.**

Fixation — chemical transformation of tissues intended to prevent subsequent decomposition, usually accomplished with formalin. Since formaldehyde is noxious, even carcinogenic, it is removed from samples by thorough washing with fresh water. To preserve samples for storage and future study, specimens are transferred to alcohol after fixation. Good fixation is important and is usually permitted to occur over many days (EMAP protocols specify at least one month).

Formaldehyde — chemically, HCHO is a gas which, when dissolved in water, is used as a fixative and is known as *formalin.*

Formalin — trademark and common name for a fixative widely used for preserving biological samples. It is commercially available as a solution of 37% w/w of *formaldehyde* in water, sometimes with methanol added. For benthic samples, formalin is used at a 10% dilution (i.e., 3.7% formaldehyde), often buffered with borax (sodium tetraborate as a saturated solution before dilution) to avoid acidic conditions that would dissolve certain biological structures and frustrate specimen identification.

Hard bottom — a bottom type consisting of rock, shell, reef material, wood or other plant material, pilings, or other firm substrata, and often colonized by *epifauna.*

Hydroid — a colonial cnidarian (relative of the sea anemone); the growth form of the animal colony (i.e., polyp stage), superficially resembles a plant.

Infauna — benthic fauna living within the sediment, often in burrows or tubes.

Invertebrates — animals without backbones, including the vast majority of marine species.

Isopod — a type of crustacean characterized by a flattened (i.e., depressed) body; includes many marine, freshwater, and terrestrial species, the latter are commonly called "pill bugs."

Macroinvertebrates — invertebrates retained on a 0.5-mm sieve or, occasionally, a 1-mm sieve. Roughly synonymous in this context with *macrofauna* and often *macrobenthos.*

Meiofauna — benthic invertebrates smaller than *macrofauna,* passing through a 0.5-mm sieve, yet retained on a 0.063-mm sieve. The larval or recruiting stages of many macrofauna also fall in this size range and are termed temporary meiobenthos. Meiobenthos are usually not considered in benthic studies for several reasons: They occur in very high abundances but are extremely difficult to sort and identify, often requiring taxonomic specialists. Special sampling, fixation, and laboratory processing is sometimes required.

Oligochaetes — a group of annelid (segmented) worms that is especially common in freshwater or oligohaline habitats (e.g., tubificids) and on land (e.g., earthworms).

Oligohaline — salinity conditions from essentially fresh water to 5 parts per thousand.

Opportunistic species — organisms usually characterized by small size, rapid growth, brief life spans, and high fecundity (numerous offspring), with fluctuating population levels extending from below to temporarily well above the carrying capacity of the environment; also termed *r-selected species. See* **equilibrium species.**

Planktonic — water-column organisms, generally microscopic, with limited swimming abilities such that currents sweep them along.

Polychaetes — a group of annelid (segmented) worms that is especially dominant in marine environments and occupies a wide range of ecological niches and habitats; also known as "bristle worms."

Preservation — usually done in ethanol or isopropyl alcohol at 75% or greater concentration. This is the medium in which macrobenthic specimens are sorted and identified and is also used for long-term storage of specimens.

Rose Bengal — a stain added to formalin fixative to give living material a bright pink color. Specimens retain this color throughout subsequent processing, thus aiding the tedious process of visually sorting animals from detrital material.

Secchi disk — a device, painted in a distinctive black-and-white pattern, used to judge transparency of the water by lowering it to the measured depth at which the disk just disappears (or reappears).

Sedentary — unattached or weakly attached, but tending not to move; see sessile.

Serpulid — a member of the polychaete family Serpulidae, which builds calcareous, often coiled or snaky, tubes or tube bundles.

Sessile — permanently attached to the substratum, not capable of moving; see sedentary.

Seston — suspended particles.

Significant effect — in reference to a hypothesis and statistical test, a significant effect is one meeting a widely recognized probability value (5% level) derived from well-established statistical methods. In the context of a quantitative and numerical analysis, the term should be used only in this sense.

Soft bottom — a bottom type consisting of mud or some other movable or workable material, often inhabited by *infauna.*

Sorting — an often-used parameter referring to the range of grain sizes in sediment. Briefly, well-sorted sediments consist of grains that are all about the same size (i.e., a narrow distribution of sizes). Beach sands are typically well sorted. Poorly sorted sediments consist of a broad range of grain sizes. Muddy sediment with sand and gravel would be termed poorly sorted.

Succession — ecological process of change in a community over time (e.g., the transformation of an open field to mature forest). Often succession represents a change in species composition from *opportunistic species* to *equilibrium species.* The organisms themselves may alter their habitat in ways that facilitate or inhibit later successional stages. Catastrophic disturbance resets the successional sequence to its earliest stages.

Taxon — a group of organisms constituting a formal biological (i.e., taxonomic) category such as species, genus, family, order, class, or phylum.

Appendix 2:
General References in Benthic Ecology and Methods

Bryant, T. L., and J. R. Pennock, eds. 1988. *The Delaware Estuary: Rediscovering a forgotten resource.* University of Delaware Sea Grant College Program.

Gray, J. S. 1981. *The ecology of marine sediments.* Cambridge.

Lalli, C. M., and T. R. Parsons. 1993. *Biological oceanography: An introduction.* Pergamon Press.

Levinton, J. S. 1982. *Marine ecology.* Prentice-Hall.

Levinton, J. S. 1995. *Marine biology: Function, biodiversity, ecology.* Oxford.

Parsons, T. R., M. Takahashi, and B. Hargrave. 1984. *Biological oceanographic processes.* Pergamon Press.

Raffaelli, D., and S. Hawkins. 1996. *Intertidal ecology.* Chapman & Hall.

Appendix 3: Useful Identification Guides and Keys

Bryant, T. L., and J. R. Pennock, eds. 1988. *The Delaware Estuary: Rediscovering a forgotten resource.* University of Delaware Sea Grant College Program.

Gosner, K. L. 1978. *A field guide to the Atlantic seashore*. Houghton Mifflin.

Kinner, P., and D. Maurer. 1978. Polychaetous annelids of the Delaware Bay region. *Fish. Bull.* 76:209–224.

Leathem, W., and D. Maurer. 1980. Decapod crustaceans of the Delaware Bay area. *J. Nat. Hist.* 14:813–828.

Lippson, A. J., and R. L. Lippson. 1997. *Life in the Chesapeake Bay*. Johns Hopkins.

Maurer, D. 1977. Estuarine benthic invertebrates of Indian River and Rehoboth Bays, Delaware. *Int. Revue ges. Hydrobiol.* 65:591–629.

Maurer, D., L. Watling, P. Kinner, W. Leathem, and C. Wethe. 1978. Benthic invertebrate assemblages of Delaware Bay. *Mar. Biol.* 45:65–78.

Pollock, L. W. 1998. *A practical guide to the marine animals of northeastern North America*. Rutgers University Press.

Ruppert, E. E., and R. S. Fox. 1988. *Seashore animals of the Southeast.* University of South Carolina Press.

Watling, L., and D. Maurer. 1973. *Guide to the macroscopic estuarine and marine invertebrates of the Delaware Bay region.* College of Marine Studies, University of Delaware, Newark.

Appendix 4:
Database Search Results

These tables display the results of the on-line searches of the Aquatic Sciences and Fisheries Abstracts (ASFA) database produced by Cambridge Scientific Abstracts, available through the University of Delaware Library. Search results below were obtained in July and September 1998.

(A) By location or place name:

Keyword(s)	Years	No. Found	Relevance or Other Comments
Delaware Bay	1993 – Present 1978 – 1993	135 229 **364**	Many studies of certain habitats and particular species (e.g., oysters, larval fish and crustaceans, horseshoe crabs, shorebirds); Maurer's many studies cited above; Curtis's trematode parasite-snail studies
Cape Henlopen	1993 – Present 1978 – 1993	16 20 **36**	Curtis's trematode parasite-snail studies; Miller's macrofauna feeding biology and groundwater seep studies; *Marenzelleria* biogeography; Bianchi's studies; and Maurer and Aprill (1979)
Cape May	1993 – Present 1978 – 1993	20 61 **81**	Various benthic studies of general interest, especially horseshoe crabs, surf clams, and hard clams, shorebirds
Broadkill	1993 – Present 1978 – 1993	0 10 **10**	Plankton; oyster shell structure; and a single invertebrate fouling study
Primehook OR Prime Hook	1993 – Present 1978 – 1993	0 0 **0**	None found
Fowler Beach	1993 – Present 1978 – 1993	1 0 **1**	A single study of horseshoe crab mating; "Fowler" alone returns hundreds of citations to Fowler's Toad!
Slaughter Beach	1993 – Present 1978 – 1993	0 0 **0**	None found
Mispillion	1993 – Present 1978 – 1993	0 0 **0**	None found
Bowers Beach	1993 – Present 1978 – 1993	0 0 **0**	None found
Murderkill	1993 – Present 1978 – 1993	0 2 **2**	Only two zooplankton studies

J. M. Lazorchak, G. B. Collins, and R. L. Graves. 1993. *Environmental Monitoring and Assessment Program (EMAP) laboratory methods manual: Estuaries.* U.S. Environmental Protection Agency, Environmental Research Library, Cincinnati, OH.

Kropp, R. K. 1994. *Delaware Bay coastline-Broadkill Beach interim feasibility study, Sussex County, Delaware: Benthic animal assessment of potential borrow source.* Draft report. U.S. Army Research Office.

Leathem, W., C. Wethe, and L. Watling. 1976. Seasonal changes of benthic invertebrate assemblages in the lightering area. Chap. 6 in *Ecological studies on benthic and planktonic assemblages in the lower Delaware Bay,* L. Watling and D. Maurer, eds. Technical report. College of Marine Studies, University of Delaware, Newark.

Levinton, J. S. 1995. *Marine biology: Function, biodiversity, ecology.* Oxford.

Lippson, A. J., and R. L. Lippson. 1997. *Life in the Chesapeake Bay.* Johns Hopkins.

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Maurer, D. 1974b. Environmental problems associated with a deepwater port in the Delaware Bay area. Vol. 1 of *Impacts of a deepwater terminal.* Technical report. College of Marine Studies, University of Delaware, Newark.

Maurer, D., and G. Aprill. 1979. Intertidal benthic invertebrates and sediment stability at the mouth of Delaware Bay. *Int. Revue ges. Hydrobiol.* 64:379–403.

Maurer, D., R. Biggs, W. Leatham, P. Kinner, W. Treasure, M. Otley, L. Watling, and V. Klemas. 1974. *Effects of spoil disposal on benthic communities near the mouth of Delaware Bay.* A report to the Delaware River and Bay Authority. College of Marine Studies, University of Delaware, Lewes.

Maurer, D., T. M. Church, C. Lord, and C. Wethe. 1985. Marine benthos in relation to pore water chemistry and sediment geochemistry of simulated dredged material. *Int. Revue ges. Hydrobiol.* 70:369–377.

Maurer, D., S. Howe, and W. Leathem. 1981. Secondary production of benthos in an industrialized estuary. *Estuaries* 4:302.

Maurer, D., S. Howe, and W. Leathem. 1992. Secondary production of macrobenthic invertebrates from Delaware Bay and coastal waters. *Int. Revue ges. Hydrobiol.* 77:187–201.

Maurer, D., R. T. Keck, J. C. Tinsman, and W. A. Leathem. 1981a. Vertical migration and mortality of benthos in dredged material. Part 1: Mollusca. *Mar. Environ. Res.* 4:299–319.

Maurer, D., R. T. Keck, J. C. Tinsman, and W. A. Leathem. 1981b. Vertical migration and mortality of benthos in dredged material. Part 2: Crustacea. *Mar. Environ. Res.* 5:301–317.

Maurer, D., R. T. Keck, J. C. Tinsman, and W. A. Leathem. 1982. Vertical migration and mortality of benthos in dredged material. Part 3: Polychaeta. *Mar. Environ. Res.* 6:49–68.

Maurer, D., R. T. Keck, J. C. Tinsman, W. A. Leathem, C. Wethe, C. Lord, and T. M. Church. 1986. Vertical migration and mortality of marine benthos in dredged material: A synthesis. *Int. Revue ges. Hydrobiol.* 71:49–63.

Maurer, D., R. T. Keck, J. C. Tinsman, W. A. Tinsman, W. A. Leatham, C. A. Wethe, M. Huntzinger, C. Lord, and T. M. Church. 1978. Vertical migration of benthos in simulated dredged material overburdens. Vol. 1 of *Marine benthos.* Tech Report D-78-35. U.S. Army Engineer Waterways Experiment Station.

Maurer, D., W. Leathem, P. Kinner, and J. Tinsman. 1979. Seasonal fluctuations in coastal benthic invertebrate assemblages. *Estuar. Coastal. Mar. Sci.* 8:181–193.

Maurer, D., and L. Watling. 1973a. *The biology of the oyster community and its associated fauna in Delaware Bay.* Delaware Bay Report Series, vol 6. College of Marine Studies, University of Delaware, Newark.

Maurer, D., and L. Watling. 1973b. Studies on the oyster community in Delaware: The effects of the estuarine environment on the associated fauna. *Int. Revue ges. Hydrobiol.* 58:161–201.

Maurer, D., L. Watling, P. Kinner, W. Leathem, and C. Wethe. 1978. Benthic invertebrate assemblages of Delaware Bay. *Mar. Biol.* 45:65–78.

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Bowers Beach	1993 – Present 1978 – 1993	0 0 **0**	None found
Murderkill	1993 – Present 1978 – 1993	0 2 **2**	Only two zooplankton studies

Appendix 4:
Database Search Results, continued

(B) By habitat, common, or author's name:

Keyword(s)	Years	No. Found	Relevance or Other Comments
Coral AND beds	1993 – Present 1978 – 1993	71 126 **197**	None relevant to Delaware's coral beds; only references to tropical coral reefs or paleoecological studies
Worm AND reef	1993 – Present 1978 – 1993	15 16 **31**	References to serpulid and sabellariid reef-forming worms, especially US Florida and West Coast species (e.g., *Phragmatopoma*)
Worm AND rock	1993 – Present 1978 – 1993	7 12 **19**	References to serpulid and sabellariid reef forming worms, especially US Florida and West Coast species (e.g., *Phragmatopoma*)
Maurer	1993 – Present 1978 – 1993	27 81 **108**	Don Maurer; benthic assessment and monitoring on Georges Bank and off southern California; many relevant references cited above
Watling	1993 – Present 1978 – 1993	20 92 **112**	Les Watling; crustacean, fisheries, and general benthic ecology, especially in the Gulf of Maine; many relevant references cited above

(C) By species or genus name:

Keyword(s)	Years	No. Found	Relevance or Other Comments
Sabellaria	1993 – Present 1978 – 1993	19 50 **69**	Sandbuilder worm; extensive literature, especially on European species, *S. alveolata;* selected citations to local species, above
Hydroides	1993 – Present 1978 – 1993	35 70 **105**	Limy tube worm; selected citations to local species, above
Schizoporella	1993 – Present 1978 – 1993	15 24 **39**	Encrusting bryozoan (moss animal); no local studies, but extensive literature on larval settlement
Astrangia	1993 – Present 1978 – 1993	6 19 **25**	Star coral; general biology, distribution, and nutritional physiology; single study of effects of sedimentation
Alcyonidium	1993 – Present 1978 – 1993	9 28 **37**	Rubbery bryozoan (moss animal) or dead man's fingers; colonization of hermit crab shells
Microciona	1993 – Present 1978 – 1993	15 27 **42**	Redbeard sponge; extensively used in laboratory biochemical studies; some older ecological literature

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