Benthic Index Development: Assessment of Ecological Status of Benthic Communities in New Jersey Marine Coastal Waters

December 2011

Prepared for:

US Environmental Protection Agency and New Jersey Department of Environmental Protection

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Preface

This report describes the development of a biotic index using macrofaunal benthic communities designed to assess the ecological condition of nearshore ocean waters along the New Jersey coast. It was compiled as part of the New Jersey Department of Environmental Protection’s (NJDEP) benthic indicators project with the goal of implementing ecosystem-based management in New Jersey’s coastal waters. Field data were collected in 2007 (August/September), 2009 (August), and 2010 (August/September). The project was sponsored by the office of Water Monitoring and Standards, NJDEP. The Institute of Marine and Coastal Sciences (IMCS) at Rutgers University, was responsible for field sampling, data assessment, and indicator development. United States Environmental Protection Agency (USEPA), Region 2 and USEPA Atlantic Ecology Division provided technical support in sampling design and index development.
Acknowledgements

This project (Development of Benthic Indicators for Nearshore Coastal Waters of New Jersey) was supported by an award from the Department of Environmental Protection, Water Monitoring and Standards, Trenton, New Jersey to Michael J. Kennish, Rutgers Project Director, Institute of Marine and Coastal Sciences (IMCS), Rutgers University, New Brunswick, New Jersey. Technical and administrative support was provided by Darvene Adams, USEPA Region 2, Edison, New Jersey, Charles Strobel, USEPA Atlantic Ecology Division, Narragansett, Rhode Island, and Robert Schuster, Department of Environmental Protection, Water Monitoring and Standards, Leeds Point, New Jersey. Special thanks are extended to Robert Connell, formerly of the Department of Environmental Protection, Water Monitoring and Standards, Leeds Point, New Jersey for his management efforts on the project. Much gratitude is extended to the anonymous experts at U.S. research institutions who volunteered their time and expertise in assigning tolerance groups to species/taxa. The committee of benthic experts at IMCS (Judith Grassle, Gary Taghon, Rosemarie Petrecca, and Charlotte Fuller) also played a major role in assigning tolerance groups, and provided valuable advice and input throughout this project.
Table of Contents

Preface ........................................................................................................................... 2

Acknowledgments ........................................................................................................... 3

List of Figures ............................................................................................................... 6

List of Tables .................................................................................................................. 8

List of Appendices ....................................................................................................... 9

Executive Summary ...................................................................................................... 12

1.0 Introduction .......................................................................................................... 15

2.0 Methods .................................................................................................................. 18
   2.1 Benthic infaunal sampling .................................................................................. 18
   2.2 Index development ............................................................................................ 20
   2.3 Expert survey and tolerance group assignments .............................................. 21
   2.4 Determination of taxa to exclude from community analyses .......................... 22
   2.5 Community analyses ....................................................................................... 23
   2.6 Biotic index determination and performance ................................................... 24

3.0 Results ..................................................................................................................... 27
   3.1 Species/taxon list .............................................................................................. 27
   3.2 Expert survey/tolerance group assignments ..................................................... 29
   3.3 Community measures 2007 and 2009 ............................................................... 33
   3.4 PCA-H community analysis (based on 500-µm mesh sieve dataset) ............... 38
   3.5 Spatial patterns and community structure: PCA-H Axes 1 & 2 ....................... 40
   3.6 Community structure: PCA Axes 1 & 2 ............................................................ 41
   3.7 Spatial patterns and community structure: PCA-H Axes 1 & 3 and 2 & 3 .......... 44
List of Figures

Figure 1 Stations sampled in New Jersey coastal waters in 2007 (black font/filled circles $n = 90$), 2009 (blue font/filled circles; $n = 43$), and in both years (2007 stations re-visited in 2009 (green font/filled circles). A single Van Veen grab ($0.04 \text{ m}^2$) was taken at each station. Red star = outfall locations, pink area = summer upwelling node; non-shaded area = non-upwelling region; letters indicate alternating non-upwelling regions and upwelling nodes from north to south (Glenn et al., 2004).

Figure 2 Frequency distribution of number of species/taxa ($n = 203$) assigned to tolerance groups I–V by each expert.

Figure 3 Percentage of species/taxa for which there is disagreement and agreement among five experts for tolerance group assignments of species/taxa on NJ list ($n = 203$). Inset indicates which tolerance groups were most often agreed upon. Colors in pie chart correspond with colors in the Table.

Figure 4 A. Frequency distribution of number of species/taxa, and B. Percentage of species/taxa assigned to tolerance groups I–V based on results from all experts combined ($n = 218$). None was assigned to group V.

Figure 5 Density of benthic fauna excluding Polygordius spp. (log number individuals $0.04 \text{ m}^2$; retained on a 500-µm sieve) at each station sampled in A. 2007 ($n = 100$; 1 grab station$^{-1}$), and B. 2009 ($n = 53$; 1 grab station$^{-1}$). Stations on x-axis listed in order of their general position along the coast (i.e., north to south), and correspond with numbers in Fig. 1. Dashed line = average (2007: 283 ind $0.04 \text{ m}^2$; 2009: 393 ind $0.04 \text{ m}^2$); pink bars = stations in upwelling nodes; white bars = stations located in non-upwelling regions; * = stations <1000 m from an outfall (in any direction); letters = alternating non-upwelling regions and upwelling nodes north to south along coast (see Fig. 1).

Figure 6 Taxon richness of benthic fauna (retained on a 500-µm sieve) at each station sampled in A. 2007 ($n = 100$; 1 grab station$^{-1}$), and B. 2009 ($n = 53$; 1 grab station$^{-1}$). Stations on x-axis listed in order of their general position along coast (i.e., north to south), and correspond with numbers in Fig. 1. Dashed line = average; pink bars = stations in upwelling nodes; white bars = stations in non-upwelling regions; * = stations <1000 m from an outfall (in any direction); letters = non-upwelling regions and upwelling nodes north to south along coast (see Fig. 1).

Figure 7 Hurlbert-Sanders rarefaction curves for infaunal community grab samples ($0.04 \text{ m}^2$) pooled across stations for 2007, 2009, and in both years.

Figure 8 PCA-H metric scaling ordination of benthic macrofaunal community spatial patterns for grab samples ($0.04 \text{ m}^2$) taken at stations ($n = 153$; 1 grab sample station$^{-1}$) in NJ coastal waters in 2007 and 2009 based on CNESS ($n = 15$ individuals). First two axes explain 18% and 10% of the variance in the data, respectively. Solid and dashed arrows indicate taxa contributing to 5% and 2% of CNESS variation in biplots, respectively. Taxa in bold indicate those with heavily weighted factor loadings ($\pm 0.5$). (A) sampling stations indicated by numbers (black font = 2007, blue and green font = 2009, bolded black font and green font with corresponding numbers = stations initially sampled in 2007 and re-sampled/re-visited in 2009, red font = stations <1000 m from an outfall for both years [in any direction], blue font with red box = dumpsite stations 2009) (also see map Fig. 1), plots B and C are the same plot where in B, black = 2007, blue = 2009 but with, (B) filled squares = stations with <5% silt clay, open squares = >5% silt clay; (C) filled squares = stations
with < 0.35% total organic carbon (TOC), open squares = > 5% TOC; (D) squares with black outline = 2007, squares with colored outline = 2009, red squares = station depth 0–7 m, blue squares = station depth 7–14 m, green square = station depth 14–23 m.

**Figure 9** PCA-H metric scaling ordination of benthic macrofaunal community spatial patterns for grab samples (0.04 m²) taken at stations (n = 153; 1 grab sample station⁻¹) in NJ coastal waters in 2007 and 2009 based on CNESS (n = 15 individuals). Axes 1 and 3 explain 18% and 8% of the variance, respectively. Solid and dashed arrows indicate taxa contributing to 5% and 2% of CNESS variation in biplots, respectively. Taxa in bold indicate those with heavily weighted factor loadings (±0.5). (A) sampling stations indicated by numbers (black font = 2007, blue and green font = 2009, bolded black font and green font with corresponding numbers = stations initially sampled in 2007 and resampled/re-visited in 2009, red font = stations <1000 m from an outfall for both years [in any direction]) (also see map Fig. 1.), (B) same plot but black = 2007, blue = 2009 with filled squares = stations with < 5% silt clay, open squares = > 5% silt clay.

**Figure 10** PCA-H metric scaling ordination of benthic macrofaunal community spatial patterns for grab samples (0.04 m²) taken at stations (n = 153; 1 grab sample station⁻¹) in NJ coastal waters in 2007 and 2009 based on CNESS (n = 15 individuals). Axes 2 and 3 explain 10% and 8% of the variance, respectively. Solid and dashed arrows indicate taxa contributing to 5 and 2% of CNESS variation in biplots, respectively. Taxa in bold indicate those with heavily weighted factor loadings (±0.5). (A) sampling stations indicated by numbers (black font = 2007, blue and green font = 2009, bolded black font and green font with corresponding numbers = stations initially sampled in 2007 and resampled/re-visited in 2009, red font = stations <1000 m from an outfall for both years [in any direction]) (also see map Fig. 1.), (B) same plot but black = 2007, blue = 2009 with filled squares = stations with < 0.35% total organic carbon (TOC), open squares = > 5% TOC.

**Figure 11** PCA-H metric scaling ordination of benthic macrofaunal community spatial patterns for grab samples (0.04 m²) taken at stations (n = 53; 1 grab sample station⁻¹) in NJ coastal waters in 2009 based on CNESS (n = 15 individuals). Axes 2 and 3 explain 12% and 9% of the variance, respectively. Solid and dashed arrows indicate taxa contributing to 5 and 2% of CNESS variation in biplots, respectively. Taxa in bold indicate those with heavily weighted factor loadings (±0.5). Sampling stations indicated by numbers (see map Fig. 1.). Red font = stations <1000 m from an outfall (in any direction); blue font with red box = former dumpsite stations.

**Figure 12** A. Frequency distribution indicating number and percentage of stations in 2007 and 2009 with biotic indices 0–7 based on finalized summary of species tolerance groups supplied by experts, B. biotic indices for 10 stations sampled in both years.

**Figure 13** Mean ±95% confidence intervals for environmental parameters and community measures (A) depth, (B) dissolved oxygen mg l⁻¹, (C) total organic carbon (%), (D) pH, (E) richness (%), and (F) density *Polygordius* spp. taken at stations in 2007 (n = 100) and 2009 (n = 53) and associated biotic index values. Note scale on y-axis differs among panels; (F) = log base 10.
List of Tables

Table 1 Summary of biotic coefficients with corresponding biotic index values, dominant ecological group, ecological quality, and community health designations modified from Borja et al. (2000).

Table 2 Reference number (ref. #) corresponding to literature citation for each study used to produce the species/taxon list for the NJ coastal ocean. Details of each study are given including: sampling dates (year), season (month when available), depth (m), salinity, gear (DC = diver cores, VV = Van Veen grab [0.04 m$^2$], SM = Smith McIntyre grab [0.1 m$^2$]), and number of stations sampled (Sta. #), number of replicate samples taken at each station (Rep. #/sta.), sieve or mesh size (sieve [µm]), identification number corresponding to group or person responsible for species/taxon identification (ID #), type of data provided by study (FL = full list, FL + ab = full list with species/taxon abundances, MB = most abundant or numerically dominant species/taxa only). n.d. = no data, unk = unknown.

Table 3 Species identified in samples taken in 2007 not present in 2009 samples. For each species the corresponding major taxonomic group, maximum density (No. ind. 0.04 m$^2$) at any station, number of stations present/sampled, and total abundance across all stations sampled are provided.

Table 4 Spearman rank correlation of environmental variables and community measures with biotic coefficients for 2007 stations ($n = 100$) and 2009 ($n = 53$). Significant correlations indicated with bold font for unadjusted and adjusted p-values (initial $\alpha = 0.05$). n.d. = no data; only significant correlations are reported.

Table 5 Comparison of 15 numerically dominant taxa (top 15) in present study (coastal New Jersey 2007/2009), and in five additional studies on the Mid-Atlantic Bight/New York Bight (MAB/NYB) inshore shelf including, (Boesch et al., 1979; Reid et al., 1991; Burlas, 2001; Valente, 2006; Grassle et al., 2009). Taxa not among top 15 in present study but among top 10 in any of the other studies are also listed (other studies top 10) for comparison including the full LEO-15 taxonomic list (+ = present, -- = absent, ? = unknown due to taxonomic designations).
List of Appendices

Appendix 1 List of stations sampled in 2007 (n = 100) with corresponding station codes used in PCA plots (Code PCA), sampling date, time arrived on station, and latitude and longitude.

Appendix 2 List of stations sampled in 2009 (n = 53) with corresponding station codes used in PCA plots (Code PCA), sampling date, time arrived on station, latitude and longitude, and qualitative observations for each sample including: sediment color, characteristics (Chara.), smell, and surface biology.

Appendix 3 Literature citations for benthic studies used to produce a list of 540 benthic macrofaunal species/taxa known to occur in NJ coastal waters. Numbers in bold correspond with reference numbers (Ref. #) given in Table 1.

Appendix 4 List of 540 benthic macrofaunal species/taxa known to occur in NJ coastal waters based on data from 18 soft-sediment studies. Sum = total number of studies each species were found in given the data available. A total of 114 species were also included from stations sampled in the 1993/1994 R-EMAP (NJ Harbor system), and EPA's 2005/2006 NCA. These are designated in bold type.

Appendix 5 Reduced list of 203 species/taxa sent to experts for assignment of tolerance groups.

Appendix 6 Instructions for experts.

Appendix 7 List of species’ synonymies sent to experts.

Appendix 8 Expert surveys with tolerance group assignments and comments.

Appendix 9 Species/taxon list (n = 218) with summarized/finalized tolerance groups used for development of a benthic index for NJ coastal ocean.

Appendix 10 Thirty-six macrofaunal species/taxa not included in community analyses for the 2007 and 2009 500-µm datasets.

Appendix 11 The R-EMAP project sampled several areas in the NY Bight Apex, as well as the NY/NJ Harbor system. Species present in the Bight Apex were directly incorporated into the NJ species/taxon list (present in Appendix 3). Species from communities in the NY/NJ Harbor system, as well as from the 2005/2006 National Coastal Assessment that met the restricted depth, salinity and sediment criteria were indirectly incorporated into the species/taxon list. Stations included are presented below.

Appendix 12 Group or person responsible for species/taxon identifications in each of 18 studies used to produce the list of benthic macrofaunal species/taxa in NJ coastal waters. Numbers in bold correspond to the ID numbers (ID #) given in Table 1.

Appendix 13 Number of individuals (total no. ind.), mean density (no. ind. 0.04 m$^2$; n = 100), standard deviation (SD), and 95% confidence interval (95% CI) for each taxon in samples taken along coastal NJ in 2007 (1 grab [0.04 m$^2$] station$^{-1}$). Based on 500-µm mesh sieve dataset. * = names that have been changed/validated based on WoRMS/ITIS (n = 37).

Appendix 14 Number of individuals (total no. ind.), mean density (no. ind. 0.04 m$^2$; n = 100), standard deviation (SD), and 95% confidence interval (95% CI) for each taxon in samples taken along coastal NJ in 2009 (1 grab [0.04 m$^2$] station$^{-1}$). Based on 500-µm mesh sieve dataset. * = names that have been changed/validated based on WoRMS/ITIS (n = 29).

Appendix 15 Density of Polygordius sp. (log number individuals 0.04 m$^2$; retained on a 500-µm sieve) at each station sampled in A. 2007 (n = 100; 1 grab station$^{-1}$), and B. 2009 (n = 53; 1 grab station$^{-1}$). Stations on
x-axis listed in order of their general position along the coast (i.e., north to south), and correspond with numbers in Fig. 1. Pink bars = stations in upwelling nodes; white bars = stations in non-upwelling regions; * = stations <1000 m from an outfall (in any direction); letters = alternating non-upwelling regions and upwelling nodes north to south along coast (see Fig. 1).

**Appendix 16** Community measures including Shannon diversity ($H'$), richness (No. taxa 0.04 m$^2$), evenness ($J'$), density (no. individuals 0.04 m$^2$), biotic coefficient, and biotic indices for each station sampled along coastal NJ in 2007 (1 grab [0.04 m$^2$] station$^{-1}$). Based on 500-µm mesh sieve dataset.

**Appendix 17** Community measures including Shannon diversity ($H'$), richness (No. taxa 0.04 m$^2$), evenness ($J'$), density (no. individuals 0.04 m$^2$), biotic coefficient, and biotic indices for each station sampled along coastal NJ in 2009 (1 grab [0.04 m$^2$] station$^{-1}$). Based on 500-µm mesh sieve dataset.

**Appendix 18** Shannon diversity ($H'$) of benthic fauna (retained on 500-µm sieve) at each station sampled in A. 2007 ($n = 100$; 1 grab station$^{-1}$), and B. 2009 ($n = 53$; 1 grab station$^{-1}$). Stations on x-axis listed in order of their general position along the coast (i.e., north to south), and correspond with numbers in Fig. 1. Pink bars = stations in upwelling nodes; white bars = stations in non-upwelling regions; * = stations <1000 m from an outfall (in any direction); letters = alternating non-upwelling regions and upwelling nodes north to south along coast (see Fig. 1).

**Appendix 19** Evenness of benthic fauna (retained on a 500-µm sieve) at each station sampled in A. 2007 ($n = 100$; 1 grab station$^{-1}$), and B. 2009 ($n = 53$; 1 grab station$^{-1}$). Stations on x-axis listed in order of their general position along the coast (i.e., north to south), and correspond with numbers in Fig. 1. Pink bars = stations in upwelling nodes; white bars = stations in non-upwelling regions; * = stations <1000 m from an outfall (in any direction); letters = alternating non-upwelling regions and upwelling nodes north to south along coast (see Fig. 1).

**Appendix 20** PCA-H metric scaling ordination of benthic assemblage spatial patterns for grab samples taken at stations ($n = 100$; 1 grab sample station$^{-1}$) along coastal NJ in 2007 based on CNESS ($n = 15$ individuals) for, (A) Axes 1 and 2, (B) Axes 1 and 3, and (C) Axes 2 and 3. Pink squares = stations in upwelling nodes, open squares = stations in non-upwelling regions (see map Fig. 1).

**Appendix 21** PCA-H metric scaling ordination of benthic assemblage spatial patterns for grab samples taken at stations ($n = 53$; 1 grab sample station$^{-1}$) along coastal NJ in 2009 based on CNESS ($n = 15$ individuals) for, (A) Axes 1 and 2, (B) Axes 1 and 3, and (C) Axes 2 and 3. Pink squares = stations in upwelling nodes, open squares = stations in non-upwelling regions (see map Fig. 1).

**Appendix 22** PCA-H metric scaling ordination of benthic macrofaunal community spatial patterns for grab samples (0.04 m$^2$) taken at stations ($n = 100$; 1 grab sample station$^{-1}$) in NJ coastal waters in 2007 based on CNESS ($n = 15$ individuals). First two axes explain 18% and 11% of variance in the data respectively. Solid and dashed arrows indicate taxa contributing to 5 and 2% of CNESS variation in biplots respectively. Taxa in bold indicate those with heavily weighted factor loadings (±0.5). Shaded/stippled areas are for illustration purposes only. (A) sampling stations indicated by numbers (see map Fig. 1). Red font = stations <1000 m from an outfall [in any direction], plots B-C are the same plot but with, (B) filled squares = stations with <5% silt clay + shading, open squares = >5% silt clay + stippling, (C) filled squares = stations with <0.35% total organic carbon + vertical stippling (TOC), open squares = >5% TOC + stippling, (D) red squares = station depth 0–7 m, blue squares = station depth 7–14 m, green square = station depth 14–23 m, shaded/stippled areas indicate sediment grain size as in B.

**Appendix 23** PCA-H metric scaling ordination of benthic macrofaunal community spatial patterns for grab samples (0.04 m$^2$) taken at stations ($n = 100$; 1 grab sample station$^{-1}$) along coastal NJ in 2007 based on...
CNESS \((n = 15\) individuals). Axes 1 and 3 explain 18% and 7% of the variance, respectively. Solid and dashed arrows indicate taxa contributing to 5 and 2% of CNESS variation in biplots respectively. Taxa in bold indicate those with heavily weighted factor loadings (\(\pm 0.5\)). Shaded/stippled areas are for illustration purposes only. (A) sampling stations indicated by numbers (see map Fig. 1). Red font = stations <1000 m from an outfall (in any direction), (B) same plot but filled squares = stations with < 5% silt clay + shading, open squares = > 5% silt clay + stippling.

Appendix 24 PCA-H metric scaling ordination of benthic macrofaunal spatial patterns for grab samples (0.04 \(m^2\)) taken at stations \((n = 100; 1\) grab sample station\(^{-1}\)) along coastal NJ in 2007 based on CNESS \((n = 15\) individuals). Axes 2 and 3 explain 11% and 7% of the variance, respectively. Solid and dashed arrows indicate taxa contributing to 5 and 2% of CNESS variation in biplots respectively. Taxa in bold indicate those with heavily weighted factor loadings (\(\pm 0.5\)). Shaded/stippled areas are for illustration purposes only. (A) sampling stations indicated by numbers (see map Fig. 2.1). Red font = stations <1000 m from an outfall (in any direction), (B) same plot but filled squares = stations with < 0.35% total organic carbon + vertical stippling (TOC), open squares = > 5% TOC + stippling.

Appendix 25 PCA-H metric scaling ordination of benthic macrofaunal community spatial patterns for grab samples (0.04 \(m^2\)) taken at stations \((n = 53; 1\) grab sample station\(^{-1}\)) along coastal NJ in 2009 based on CNESS \((n = 15\) individuals). (A) Axes 1 and 2 explain 26% and 12% of the variance, respectively, (B) Axes 1 and 3 explain 26% and 9% of the variance respectively. Solid and dashed arrows indicate taxa contributing to 5 and 2% of CNESS variation in biplots respectively. Taxa in bold indicate those with heavily weighted factor loadings (\(\pm 0.5\)). Sampling stations indicated by numbers (see map Fig. 1). Red font = stations <1000 m from an outfall (in any direction); blue font with red box = former dumpsite stations.

Appendix 26 Frequency distribution indicating the number of stations in (A) 2007 \((n = 100)\), and (B) 2009 \((n = 53)\) with biotic indices 0-7 based on the summary of species tolerance scores \((n = 200)\) supplied by experts (summary), and by each expert (1-5) independently.

Appendix 27 Water column parameters for each station sampled in 2007 including depth (m), temperature (\(^{\circ}\)C), salinity, pH, SpCond, dissolved oxygen (ml L\(^{-1}\)), dissolved oxygen charge, turbidity, and chlorophyll \(a\).

Appendix 28 Water column parameters for each station sampled in 2009 including depth (m), temperature (\(^{\circ}\)C), salinity, pH, SpCond, and dissolved oxygen (ml L\(^{-1}\)). n.d. = no data.

Appendix 29 Sediment parameters for each station sampled in 2007 including silt clay (%), sand (%) and TOC (total organic carbon) content.

Appendix 30 Sediment parameters for each station sampled in 2009 including silt clay (%), sand (%) and TOC (total organic carbon) content.
Executive Summary

The benthic sampling conducted during this project, as part of the US Environmental Protection Agency's National Coastal Assessment (NCA) program, is the most spatially and temporally (i.e., yearly) comprehensive survey that has been conducted on benthic communities in New Jersey's nearshore ocean waters (shore to 3 nm offshore). The sampling was designed to take into account the complexity of New Jersey's coastal waters with its episodic natural upwelling zones, offshore wastewater discharges, and the State's management zones. A relatively large total area was sampled (6 m²), with 153 stations distributed along the Atlantic coastline from Sandy Hook to Cape May in 2007 and 2009. An additional 100 samples taken in 2010 are pending analysis (samples not sorted or identified). This extensive survey provided up-to-date information on macrofaunal species/taxon composition, diversity, and abundance with a total of 113,117 individuals belonging to 273 species/taxa found over both years (based on data modified for community analysis). Prior to this, the most complete macrofaunal data available sampled a total area of <0.9 m², and reported 43,923 individuals belonging to 148 species/taxa (Grasse et al., 2009). Most importantly, significant progress was made towards the development of a biotic index to assess the ecological quality and benthic community health of New Jersey's nearshore ocean waters. Complementary environmental and biological data allowed for an integrative approach to index development and assessment of ecological status by providing insight into factors important in influencing macrofaunal community composition and spatial variability in the relatively little-studied, highly mobile, sandy sediments, typical of energetic inner-shelf environments.

The ten numerically dominant species/taxa in 2007 included: the polychaetes *Polygordius* spp., *Prionospio pygmaeus*, *Tharyx* sp. A, and *Aricidea catherinae*; the oligochaetes *Naidinae* sp. 2, *Grania longiducta*, *Peosidrilus coeloprostatus*, and *Tubificoides* sp. 1; the amphipod *Protohaustorius deichmannae*; and the bivalve *Nucula proxima*. The same species/taxa dominated assemblages in 2009 with the exception of *P. pygmaeus*, *P. coeloprostatus*, and *Naidinae* sp. 2 which were replaced among the top ten by two capitellid polychaetes, *Amastigos caperatus* and *Mediomastus ambiseta*, and the bivalve *Angulus agilis*. There were 71 species/taxa in 2007 that were not sampled in 2009, and 23 species/taxa in 2009 that were not sampled in 2007. The majority of these were rare, and present at very low densities (<10 ind. 0.04 m²).

*Polygordius* spp., was numerically dominant species making up 34% of the macrofaunal density in 2007 (\(\bar{x} = 148 \pm 87\) CI ind. 0.04 m²; range: 0–2603 ind. 0.04 m²), and 70% of macrofaunal density in 2009 (\(\bar{x} = 925 \pm 598\) CI ind. 0.04 m²; range 0–10,942 ind. 0.04 m²). Density of taxa excluding *Polygordius* spp. was relatively higher at stations sampled in 2009 (\(\bar{x} = 393 \pm 137\) CI ind. 0.04 m²; range: 26–3213 ind. 0.04 m²) compared to 2007 (\(\bar{x} = 283 \pm 45\) CI ind. 0.04 m²; range: 36–1568 ind. 0.04 m²).

Fewer species/taxa were sampled in 2009; however, species richness among stations was similar between the two years (2007: \(\bar{S} = 25 \pm 1.7\) CI taxa 0.04 m²; range 4–44 taxa 0.04 m²; 2009: \(\bar{S} = 25 \pm 2.4\) CI ind. 0.04 m²; range: 9–46 taxa 0.04 m²). Taxon diversity and evenness were slightly higher in 2007 (\(H' \bar{x} = 2.02 \pm 0.11\), \(J' \bar{x} = 0.64 \pm 0.03\)) compared to 2009 (\(H' \bar{x} = 1.64 \pm 0.18\), \(J' \bar{x} = 0.52 \pm 0.06\)). Hurlbert-Sanders rarefaction curves indicate that stations sampled in 2009 had a lower overall diversity in comparison to those sampled in 2007. None of the curves leveled off at a fixed number of species/taxa indicating that diversity might increase with additional sampling.
There were no visible trends in any of the community measures in relation to summer upwelling nodes (areas along the coast that may experience hypoxic conditions; (Glenn et al., 2004), distance from an outfall, or with position (north to south) along the coast. Total density and richness of benthic macrofauna were significantly (p = <0.0001) and positively correlated with water depth in both years.

The projection of PCA-H Axes 1 and 2 accounted for the most variation in community composition, explaining 18% and 11% of the variation in 2007. The projection of these axes best illustrates the differences in community composition between different sediment types/properties (i.e., grain size and total organic carbon [TOC]), and water depths. The projection of the PCA axes 1 and 2 for the 2009 infaunal data explained 26% and 12% of the variation in community composition, respectively, and also showed differences in community composition with sediment grain size, and water depth. Principal components analysis of combined 2007/2009 infaunal data produced similar results to those observed for 2007. However, the grouping of samples/stations based on <5% or >5% silt clay along PCA Axis 1 was less clear for the combined 2007/2009 data. Several samples/stations in 2009 with <5% silt clay content grouped with samples/stations from 2007 having >5% silt clay. The taxa most responsible (accounting for 2–5% of the variation) for the separation of samples/stations in each of these plots is discussed in detail in the Results section.

Results based on community measures and multivariate analyses of macrofaunal species composition and abundance did not support the declaration of 100% impairment of New Jersey's nearshore ocean waters based on dissolved oxygen levels below 5 mg L⁻¹ (see Discussion for details). However, in 2009 the projection of PCA-H Axes 2 and 3 identified several samples/stations arranged along Axis 2 in the lower right hand quadrant that contained an assemblage of species/taxa not present in PCA-H analysis of the 2007 and 2007/2009 data. This community was dominated by several Oligochates (T. gabriellae, Tubificoides sp.1., and G. longiducta), the bivalve N. proxima, and the three polychaetes including a cirratulid Tharyx sp., capitellid M. ambiseta, and a syllid P. longicirrata. This may indicate initial signs of degradation, and should be monitored in future assessments (see Discussion for details).

A total of 19 studies on benthic soft-sediment fauna were used to compile the initial list of 540 benthic macrofaunal species/taxa that occur along the New Jersey coast. Tolerance groups were assigned to a total of 218 species/taxa. Of these 81%, (177/218 species/taxa) were considered sensitive or indifferent (tolerance groups I and II, respectively), 16% (34 species/taxa) were tolerant but also present under "natural conditions" (III), and 3% (6 species/taxa) were second order opportunistic species (IV). No species were determined to be first order opportunistic species (V).

The initial application of the biotic index indicated that 28% of stations sampled over both years were unpolluted (BI = 0 & 1), containing a relatively high proportion of species/taxa that are sensitive to organic enrichment representing a "normal or impoverished" community. The remaining 74% of stations also had a relatively high ecological status, classified as being slightly polluted (BI = 2). These communities contained a high proportion of species/taxa that are relatively tolerant of organic enrichment but are also known to occur under "normal" conditions.

In an attempt to assess index performance, the level of agreement between the biotic indices determined in the present study, and other biotic metrics was also examined. The Paul et al. (2001) index also classified 27% and 73% of stations in 2007 as reference and degraded, respectively;
however, there was little agreement between the two indices with regard to individual station classifications. Using the present study's index 10, 50, and 40% of the stations classified as reference in the REMAP study were determined to be unpolluted, slightly polluted, and meanly polluted, respectively. In contrast, none of the stations classified as impacted in the REMAP study were considered as reference when the biotic index was applied, with 55 and 45% of impacted stations being classified as slightly or meanly polluted. Such comparisons between the biotic index of the present study, and other biotic metrics were determined to be inappropriate due to the different scales of classification employed (i.e., biotic index = 7 levels and Paul et al. (2001) and REMAP indices only had 2 levels), and the high proportion species/taxa and individuals in the REMAP study were excluded from the calculation because tolerance groups had not been assigned. Thus, even though REMAP stations selected were within the depth, salinity and grain size ranges specified in the present study, benthic macrofaunal species composition in coastal estuaries differed from the NJ coastal ocean.

There was 67% agreement among expert assignments of an index value (0 to 7) to a test set of 15 stations (sampled in either 2007 or 2009), based on species/taxon composition, community measures, and environmental parameters. Classifications based on the summarized expert values (determined by majority agreement among assignments) agreed with the calculated biotic index for 60% of the stations examined. For those assignments that were not in agreement (6 stations), 67% of the time (4 stations out of 6) experts provided a value that was one step higher (+1) than the calculated one (i.e., 2 [expert] vs. 1 [calculated]).

Biotic coefficients used to determine the discrete biotic index value (0 to 7) were significantly and positively correlated with water depth, species/taxon richness, and density of *Polygordius* spp. in 2007 and 2009 following the p-value adjustment for multiple comparisons. Considering the unadjusted p-values, total organic carbon was also significantly and positively correlated with index values, whereas, dissolved oxygen, and pH were significantly and negatively correlated.

Although the biotic indices for benthic community condition were in general agreement with those provided by community analyses, the main findings of this study have been primarily based the latter. Moreover, the dissolved oxygen criterion of 5 mg L\(^{-1}\) that was used in an assessment that reported 100% of New Jersey's ocean waters to be impaired due to hypoxia is well above the concentration expected to have a severe impact on benthic communities, and results of the present study confirm this (see Discussion for details). Although significant progress was made in developing a benthic index for the New Jersey coastal ocean with very positive findings related to its performance, results should be interpreted with caution until the index is further calibrated and properly validated.
1.0 INTRODUCTION

New Jersey's coastal marine environment is potentially subject to impacts from several natural and human sources such as episodic coastal upwelling (Glenn et al., 2004); pollutants, organic matter, and fresh water discharged from the southerly flowing Hudson river plume (Hunter et al., 2010); and wastewater discharges to nearshore waters. An Integrated Assessment in 2002 and 2004 reported that 70% and 100% of New Jersey's ocean waters, respectively, were impaired due to hypoxia, based on a dissolved oxygen criterion of 5 mg L\(^{-1}\) (Connell, 2007; Balthis et al., 2009), however, no large-scale or multi-species fish kills were apparent (Connell, 2007). The effects of these and other impacts need to be placed within the context of ecosystem health. One way to accomplish this, is by using soft-sediment, benthic communities as indicators of ecological condition. Benthic invertebrates can provide a biologically meaningful measure of ecological quality in comparison to abiotic physical or chemical parameters, for which little information is often available in regard to the biological impact of different types and levels of disturbance to a system. Being relatively long-lived, sedentary in their juvenile and adult phases, and intimately associated with the sediment in which they live, benthic invertebrates respond predictably to anthropogenic and natural stress (Pearson and Rosenberg, 1978; Dauer, 1993). Their inclusion in marine monitoring assessments has expanded greatly over the last decade, as benthic indices have become more prevalent (e.g., Marques et al., 2009).

The United States Environmental Protection Agency's (USEPA) National Coastal Assessment (NCA) program, implemented through a federal-state partnership, is working toward providing the states and the nation with the first complete and consistent dataset on the condition of benthic communities; however, efforts so far have mainly focused on estuarine systems (Connell, 2007). The present work, which was initiated and supported by the NJDEP, is being conducted to
extend ecosystem-based assessment to the nearshore ocean waters of the State. Prior to this, the ecological health of New Jersey's coastal waters was solely based on dissolved oxygen measurements, and there was no comprehensive dataset for benthic communities in coastal waters. The main purpose of the present study was to investigate whether this hypoxia (5 mg L\(^{-1}\)) adversely affects benthic communities, and to develop a benthic index (BI) specifically designed to quantitatively assess the ecological status of New Jersey's coastal marine waters (Strobel et al., 2008).

To accomplish this, an extensive literature search was undertaken to identify major existing sources of benthic community data for New Jersey's nearshore ocean waters, and determine data gaps/needs. Workshops with a panel of experts were held to assess the data, discuss a sampling design for the field survey, and to determine the most appropriate benthic index/metric to be developed/implemented given the data available, and current knowledge of the habitat (e.g., summary for the November 2006 workshop can be found at: http://www.crssa.rutgers.edu/projects/jcgis/ca/study.html). A probabilistic survey design was employed to allow for an assessment of 100% of the State’s coastal waters out to 3 nm offshore using modified NCA sampling methods. This approach took into account the multiple upwelling zones located along the New Jersey coast, historically associated with recurrent seasonal hypoxia (Glenn et al., 2004), as well as several offshore dischargers. A multimetric index was selected that combines several measures of community response to "stress" (e.g., organic enrichment) into a single index. The AMBI, AZTI's Marine Biotic Index, originally developed for European estuaries and coastal environments was the index chosen for modification and adaptation to the NJ coastal ocean. The AMBI has been applied in the assessment of 'Ecological Status', under the European Water Framework Directive (Borja et al., 2003; Borja, 2004; Borja et al., 2004) which aims to
achieve 'good water status' for all member states by 2015. It is based on the proportion of species assigned by experts (using best professional judgment) to one of five ecological groups according to their sensitivity/tolerance to increasing levels of sedimentary organic matter/stress (Grall and Glémarec, 1997).

To fulfill data needs for index development, and to obtain insight into natural sources of spatial and temporal variability in infaunal communities in the physically active, sandy sediments along coastal NJ, extensive benthic surveys were conducted in 2007 (August/September), 2009 (August), and 2010. In an effort to validate the index, several stations in 2009 and 2010 (results not yet available for 2010) targeted potentially impacted areas, to assess the robustness/sensitivity of the index. Species composition and abundance data from these surveys, and from previous studies in non-impacted and variably impacted areas were examined to compile a list of commonly encountered species along coastal NJ. Working toward the development of a modified AMBI, benthic experts were identified, and asked to assign these species to tolerance/ecological groups. Following a critical examination of assignments, the biotic index was calculated for each of the stations surveyed in 2007 and 2009.

This study presents the first application of the modified AMBI to assess the ecological quality and benthic community health of nearshore ocean waters in NJ. These results are examined in relation to those provided by multivariate (i.e., Principal Components Analysis, PCA), and community measures (e.g., diversity, richness, rarefaction), as well with several environmental parameters measured during benthic surveys (e.g., sediment grain size distribution and organic carbon content, dissolved oxygen, distance from wastewater outfall, depth etc.) to provide a comprehensive, integrative approach to index development, and to critically assess index performance. Recommendations for index validation and further index development are provided to
improve index performance, and to allow accurate future assessments as the basis for management decisions.

2.0 METHODS

2.1 Benthic infaunal sampling

Benthic sampling was conducted during the months of August and September in 2007, 2009 and 2010 throughout New Jersey's nearshore ocean waters (<3 nm) extending from Sandy Hook to Cape May (Fig. 1; Appendices 1–2). Infaunal samples were taken using a 0.04-m² Van Veen grab, processed over stacked 300 and 500 µm mesh sieves, and fixed in 10% formalin solution (see Connell, [2007] for further details). In 2007, samples were taken at 100 randomly selected stations (Sta. No. 1–100) which resulted in seven samples being located within 1000 m of an outfall, but not closer than 100 m, in any direction. Fifty-three stations were sampled in 2009 including: 30 "new" randomly selected stations (Sta. No. 101–130), 10 randomly selected stations previously sampled in 2007 (referred to as re-visited stations; Sta. No. 10, 18, 24, 29, 38, 66, 70, 73, 84, 95), 2 stations at the former 6-Mile Dumpsite (Sta. No. 131–132), 2 stations at the former 12-Mile Dumpsite (Sta. No. 133–134), and 9 stations just outside the mixing zone (~100 m away from an outfall discharge in any direction; Sta. No. 135–143), (Fig. 1). The 10 re-visited stations and 30 "new" stations were included to examine temporal variability in benthic community structure, whereas, stations just outside the mixing zone and at the former dumpsites were taken in an effort to sample an impacted benthic community. Sampling in 2010 was conducted within the mixing zone (the area within 100 m of the outfall effluent discharge in any direction) at several discharge locations, however, samples have not yet been sorted/identified.
Figure 1 Stations sampled in NJ coastal waters in 2007 (black font/filled circles n = 90), 2009 (blue font/filled circles; n = 43), and in both years (2007 stations re-visited in 2009 (green font/filled circles; n = 10). A single Van Veen grab (0.04 m²) was taken at each station. Red star = outfall
locations, pink area = summer upwelling node; non-shaded area = non-upwelling region; letters indicate alternating non-upwelling regions and upwelling nodes from north to south (Glenn et al., 2004).

2.2 Index Development

Compilation of a species/taxon list for benthic macrofaunal communities in NJ nearshore ocean waters

A species/taxon list to be used in development of a benthic index for the New Jersey coastal ocean was compiled using multiple benthic datasets from previously sampled non-impacted and variably impacted locations on the NY/NJ coast (Appendix 3–4). Benthic samples taken in 2007 and 2009 ($n = 153$) in the present study also provided an invaluable and up-to-date source of information on macrofaunal species/taxon composition and abundance. Datasets utilized were generally restricted to areas with depths of 2–51 m (based on Boesch et al. (1979)), salinities of 26–36, and coarse sandy sediments ($\leq 40\%$ silt clay), which are characteristic of the NJ coastal environment. To facilitate cross study comparisons the validity of each species/taxon was updated with their current taxonomic status according to WoRMS and/or ITIS. The initial list that was compiled had to be reduced because it contained too many species/taxa to send to experts (see Results section). Thus, in an effort to ensure that the commonly encountered species/taxa in NJ coastal waters were included in the final list that was sent to experts for assignment of tolerance groups (ecological groups I–V), only species/taxa that were present in three or more of the 18 studies examined (present in at least 16% of the studies) were retained. The list was further reduced on the advice of a committee of benthic experts at the Institute of Marine and Coastal Sciences (IMCS), Rutgers University. Organisms removed included highly mobile epifaunal species (i.e., *Crangon septemspinosa*: a shrimp that undergoes seasonal migrations; *Ovalipes ocellatus*: a swimming crab; *Dulichia porrecta*, *Microprotopus raneyi*, *Photis macrocoxa*, *Photis reinhardinow Photis pollex*: epifaunal caprellid
shrimps), and species typically found on hard substrates (*Mytilus edulis*: a mussel). Five higher taxonomic groups were included: *Capitella* spp., *Polygordius* spp., Oligochaeta spp., Nemertina spp., and Sipuncula spp. A reduced list of 203 species/taxa sent to experts for assignment of tolerance groups is found in Appendix 5.

### 2.3 Expert survey and tolerance group assignments

A survey document was prepared outlining a procedure for assigning tolerance groups (ecological groups I–V) to species/taxa to an increasing stress gradient (i.e., increasing organic matter enrichment) following Grall and Glémarec (1997), and Borja et al. (2000). The committee of benthic experts at IMCS was the first to complete this survey, and collectively assigned tolerance groups to 203 species/taxa. Results from this group effort were treated as if they came from a "single expert." This group also provided feedback pertaining to any modifications that could be made to improve the survey prior to sending it to 13 anonymous experts at other US research institutions. Survey details are presented in Appendices 6–7 including instructions to experts, and a list of species’ synonymies to aid experts in recognizing species names that may have been changed over time, respectively.

Survey results (see Appendix 8) were compiled and examined by the IMCS committee to determine tolerance groups for any species/taxon for which there was little agreement among experts, and to provide some “quality control” for the species/taxa where tolerance groups had been agreed on. This was done by examining the “comment” section of the survey where experts were asked to explain the reasoning for their tolerance group assignments for each species/taxon. The committee gave more weight to tolerance group assignments that were based on some form of experience or literature citation for the species or higher taxonomic group, rather than those based on “guesses.” In some cases the committee took an average of the group assignments. The committee
also incorporated their own knowledge/experience into the final decision. Thus, during this process
tolerance assignments may have been changed even for those species/taxa where there had originally
been agreement among the experts. The committee also decided that three of the higher taxonomic
groups (i.e., Oligochaeta spp., Nemertina spp. and Sipuncula spp.) should be excluded because they
were not confident in assigning any one tolerance level to a taxon representing a large number of
highly variable species. Species/taxon tolerance designations provided by experts were compared
using frequency distributions and pie charts. Another 18 species/taxa found to be notably abundant
along coastal NJ were assigned tolerance groups by the IMCS committee following the second
benthic survey in 2009. These results were analyzed separately (for further information see Results).
The final list of species/taxa with assigned tolerance groups is found in Appendix 9.

2.4 Determination of taxa to exclude from community analyses

A total of 305 taxa (300-µm mesh sieve) and 275 taxa (500-µm mesh sieve) were identified in grab
samples taken in NJ waters in 2007. Forty-three and 36 taxa were removed from the 300-µm and
500-µm datasets, respectively, prior to community analysis. Stations sampled in 2009 contained 222
taxa, and 36 were removed prior to community analysis (500-µm mesh sieve). Taxon composition
was again slightly modified in order to produce a single list of taxa for 2007 and 2009 for PCA. The
majority of taxa removed included higher taxonomic categories (e.g., Oligochaeta, Lumbrineridae)
consisting of unidentifiable individuals likely belonging to a taxonomic category already included in
the list (a redundant taxon), but which could not be identified because they were damaged or were
juvenile stages etc. Taxa such as Naidinae sp. 1, Naidinae sp. 2, and Naidinae sp. 3 were retained
because they represented three different species of Oligochaeta, but the taxon Naidinae was removed
because it was considered redundant. Given the large number of individuals in the taxon Nemertina
spp. compared to the few species identified, this group was retained because it likely includes at least
one species not already present in the list. Species/taxa known to reside even partly submerged in sediments were also retained. Appendix 10 lists taxa removed prior to community analyses for both years. The total abundance of benthic fauna sampled in 2007 and 2009 was 47,434 individuals (43,182 following the removal of redundant taxa), and 80,509 individuals (70,033 following removal of redundant taxa), respectively. Community analyses were conducted on these modified datasets. Since results did not differ substantially between the 300-µm versus the 500-µm mesh datasets, analyses presented here are for benthos retained on the 500-µm mesh sieve only.

2.5 Community analyses

Community composition was compared among stations (based on individual grab samples [i.e., grab samples were not averaged or pooled]) in NJ coastal waters in 2007 and 2009 (Fig. 1) using CNESS (Chord Distance Normalized Expected Species Shared) as described by Trueblood et al. (1994). CNESS is a faunal index based on an extension of Orloci (1978), and Grassle and Smith (1976) NESS (Normalized Expected Species Shared). This analysis produces a dissimilarity matrix from a sample-by-species matrix, and is based upon the number of expected species shared in a random draw of n individuals (n = 15) from n stations (2007 n = 100; 2009 n = 53; combined 2007/2009 n = 153). This particular index was chosen because it is sensitive to rare as well as abundant species. To provide a more comprehensive and informative presentation of the data, a metric scaling of CNESS was performed in Matlab programs written by Dr. Eugene D. Gallagher, UMASS/Boston (see http://alpha.es.umb.edu/faculty/edg/files/edgwebp.htm). The metric scaling of CNESS converts the sample-by-species matrix to a normalized hypergeometric probability matrix (H), which describes the probability of sampling each species in each grab sample with a random draw of 15 individuals. This hypergeometric matrix is then analyzed by Principal Components (PCA-H). The first two scores from the PCA-H provide a two-dimensional metric scaling of CNESS
distances among samples representing the best least-squares fit for the data. This plot is very similar to that produced by non-metric multidimensional scaling (NMDS), but the advantage of the metric scaling is that CNESS distances among samples are preserved. Thus, species that contribute to CNESS variation among samples can then be displayed in a Gabriel Euclidean distance biplot overlay (Gabriel, 1971), where the length and angle of species vectors indicate the contribution of the species to the PCA-H axes. Species that contributed ≥ 2% to CNESS variation were included in the biplots.

Community measures including Shannon Diversity (H'; base e), richness, evenness (J'), and density including and excluding *Polygordius* spp. (total individuals 0.04 m⁻¹) were determined and plotted for each of the coastal stations in both years. Diversity was also examined using Sanders-Hurlbert rarefaction curves (Sanders, 1968; Hurlbert, 1971) based on grab samples for each station and pooled across stations in 2007 (n = 100), 2009 (n = 53), and combined 2007/2009 (n = 153). Differences in community measures between years, and between upwelling and non-upwelling nodes, were tested using a non-parametric Mann-Whitney U test (α = 0.05).

### 2.6 Biotic Index determination and performance

Biotic index values (0–7) were determined for each station sampled in 2007 and 2009 using the following formula proposed by Borja et al. (2000):

\[
\text{Biotic coefficient (BC)} = (0 \times \% \text{GI}) + (1.5 \times \% \text{GII}) + (3 \times \% \text{GIII}) + (4.5 \times \% \text{GIV}) + (6 \times \% \text{GV})
\]

\[
\frac{}{100}
\]

where GI–GV are tolerance groups assigned to species/taxa by experts based on their sensitivity to increasing levels of sedimentary organic matter enrichment as outlined by Grall and Glémarec (1997), (see Appendix 6). Biotic coefficients are a continuous parameter with values between 0 and 6, which are translated into a discrete biotic index value ranging from 0 (i.e., unpolluted/normal
conditions) to 7 (i.e., extremely polluted/azoic conditions) based on the relative abundance of each ecological group (EG), (Table 3).

**Table 1** Summary of biotic coefficients with corresponding biotic index values, dominant ecological group, ecological quality, and community health designations modified from Borja et al. (2000).

<table>
<thead>
<tr>
<th>Biotic coefficient (BC)</th>
<th>Biotic Index</th>
<th>Dominant ecological group (EG)</th>
<th>Ecological quality</th>
<th>Community health</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 &lt; BC ≤ 0.2</td>
<td>0</td>
<td>I</td>
<td>unpolluted</td>
<td>normal</td>
</tr>
<tr>
<td>0.2 &lt; BC ≤ 1.2</td>
<td>1</td>
<td>unpolluted</td>
<td>impoverished</td>
<td></td>
</tr>
<tr>
<td>1.2 &lt; BC ≤ 3.3</td>
<td>2</td>
<td>III</td>
<td>slightly polluted</td>
<td>unbalanced</td>
</tr>
<tr>
<td>3.3 &lt; BC ≤ 4.3</td>
<td>3</td>
<td>meanly polluted</td>
<td>transitional to pollution</td>
<td></td>
</tr>
<tr>
<td>4.3 &lt; BC ≤ 5.0</td>
<td>4</td>
<td>IVV</td>
<td>meanly polluted</td>
<td>polluted</td>
</tr>
<tr>
<td>5.0 &lt; BC ≤ 5.5</td>
<td>5</td>
<td>heavily polluted</td>
<td>transition to heavily polluted</td>
<td></td>
</tr>
<tr>
<td>5.5 &lt; BC ≤ 6.0</td>
<td>6</td>
<td>V</td>
<td>heavily polluted</td>
<td>heavily polluted</td>
</tr>
<tr>
<td>Azoic</td>
<td>7</td>
<td>Azoic</td>
<td>extremely polluted</td>
<td>azoic</td>
</tr>
</tbody>
</table>

Species present in samples taken in 2007 and 2009, but not assigned a tolerance group in the present study, were excluded from the calculation of the biotic coefficient/biotic index. Therefore, they were not taken into account in determining the ecological quality and health of infaunal communities. For each station, the percentage of the total number of species, and the total number of individuals not included in the biotic index calculation, was determined (as recommended by Borja and Muxika 2005). In the initial application/calculation of the index, the proportion of species and individuals excluded was found to be too high (see Results section 3.8) based on recommendations provided in Borja and Muxika (2005); thus, tolerance groups were assigned for an additional 18 commonly abundant species/taxa by the IMCS expert committee. This initial calculation was based on the tolerance groups assigned to 200 potential species/taxa, and the biotic index values obtained were compared among experts, based on their individual tolerance group designations, and the finalized summary. Following the assignment of tolerance groups to 18 species/taxa, the index was recalculated based on 218 potential species/taxa (including the original 200 plus the 18 additional
species/taxa), and these values were then used in the assessment of infaunal community health for this report (Appendix 9).

Non-parametric correlations of environmental factors and community measures for 2007 and 2009 with biotic coefficients were performed in SPSS 10. Only significantly correlated factors were reported, and the Holm-Bonferroni correction was applied to p-values to correct for multiple comparisons. Both corrected and un-corrected ($\alpha = 0.05$) significant correlations are presented. Means with $\pm 95\%$ confidence intervals for significant environmental factors and community measures were also plotted against biotic index values for the 2007 and 2009 stations/samples.

The finalized biotic index values for the 10 stations sampled in both years (10 stations sampled in 2007 and then re-visited/sampled in 2009) were compared. The level of agreement between results based on the biotic index of the present study, and other biotic metrics, was also examined. For this analysis, the index outlined in Paul et al. (2001), created for estuaries in the Virginian Biogeography Province, was used to classify the 2007 stations as either reference or degraded. Results provided by the biotic index in the present study were also compared for 52 stations sampled as part of the 1993/1994 REMAP program which had been classified as either reference/non-impaired ($n = 20$), impacted ($n = 11$), or unclassified ($n = 21$). These stations were within the restricted depth, salinity, and sediment ranges specified for this study (see methods section 2.2). The level of agreement between the calculated biotic index values, and the same series of values assigned by experts (IMCS committee), was examined for 15 stations selected from the 2007 and 2009 surveys. Stations were selected to include a wide range of species assemblages (based on PCA), and sediment parameters (e.g., grain size, TOC). For each station, experts were given information pertaining to species composition, density, diversity, richness, evenness, depth, salinity, dissolved oxygen, grain size and total organic carbon, and asked to use this information to
determine the ecological quality/infaunal community health for each station by assigning biotic index values 1–7 based on Table 3 above.

3.0 RESULTS

3.1 Species/taxon list

A total of 19 studies on benthic soft-sediment fauna were used to compile the initial list of 540 benthic macrofaunal species/taxa in New Jersey coastal waters (see Table 2; Appendix 4 for full species/taxa list). Studies included both non-impacted and variably impacted locations from 1973–2007 (sieve size 300-µm or 500-µm). A full species/taxon list with corresponding abundance data was available for some studies, whereas others only reported a full or partial list of species/taxa (usually the most abundant/dominant) without abundances (Table 2). Fewer datasets were available from studies in areas with impacted/compromised benthic communities, and many were conducted one or more years following the initial impact-contamination. These included the sewage sludge dumpsite (Sta. 7), sewage accumulation area (Sta. 6), and the northern Christiansen Basin (Sta. 1, 5.6 km NW of sewage dumpsite with an enriched assemblage in Reid et al. [1991]; 4–6 mile mud dumpsite/dredged material dumpsite in Valente (2006); a compromised area at the mouth of Delaware Bay with relatively high salinity (Sta. 57, the most polluted station closest to the mouth of the bay in Hartwell et al. [2001]; and an area off coastal NY/NJ where an oxygen depletion event occurred in 1976 (Steimle and Radosh, 1979). Additionally, benthic data from stations sampled during the 1993/1994 Regional Environmental Monitoring and Assessment Program (R-EMAP), (e.g., Adams et al. (1998); Delaware Bay, Hartwell et al. (2001), and EPA's 2005/2006 NCA (National Coastal Assessment: NCA) were directly or indirectly incorporated into the species/taxon list (a total of 114 species were included). Twelve of these stations had been designated as impacted
based on the REMAP (NCA algorithm). A list of stations and specifics as to how these data were managed and incorporated into the NJ coastal species/taxon list is discussed in detail in Appendix 11.

Table 2 Reference number (ref. #) corresponding to literature citation for each study used to produce the species/taxon list for the NJ coastal ocean. Details of each study are given including: sampling dates (year), season (month when available), depth (m), salinity, gear (DC = diver cores, VV = Van Veen grab [0.04 m$^2$], SM = Smith McIntyre grab [0.1 m$^2$]), and number of stations sampled (Sta. #), number of replicate samples taken at each station (Rep. #/sta.), sieve or mesh size (sieve [µm]), identification number corresponding to group or person responsible for species/taxon identification (ID #), type of data provided by study (FL = full list, FL + ab = full list with species/taxon abundances, MB = most abundant or numerically dominant species/taxa only). n.d. = no data, unk = unknown.

<table>
<thead>
<tr>
<th>Ref. (#)</th>
<th>Sampling dates/year</th>
<th>Season</th>
<th>Depth (m)</th>
<th>Sal.</th>
<th>Gear</th>
<th>Sta. (#)</th>
<th>Rep. (#/Sta.)</th>
<th>Sieve (µm)</th>
<th>ID (#)</th>
<th>Data type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1996−2004</td>
<td>n.d.</td>
<td>13−16</td>
<td>n.d.</td>
<td>DC</td>
<td>2</td>
<td>36/36</td>
<td>300 &amp; 500</td>
<td>5</td>
<td>FL</td>
</tr>
<tr>
<td>2</td>
<td>2007</td>
<td>Aug−Sep</td>
<td>2−23</td>
<td>26−33</td>
<td>VV</td>
<td>100</td>
<td>1</td>
<td>300 &amp; 500</td>
<td>5</td>
<td>FL+ab</td>
</tr>
<tr>
<td>3</td>
<td>1993−1994</td>
<td>Aug−Oct</td>
<td>6−41</td>
<td>28−36</td>
<td>VV</td>
<td>28</td>
<td>2</td>
<td>500</td>
<td>6</td>
<td>FL+ab</td>
</tr>
<tr>
<td>4</td>
<td>1994−1995</td>
<td>spring−fall</td>
<td>12−16</td>
<td>34</td>
<td>DC</td>
<td>3</td>
<td>9/18/18</td>
<td>300</td>
<td>2</td>
<td>FL+ab</td>
</tr>
<tr>
<td>5</td>
<td>1997</td>
<td>Sep</td>
<td>5−19</td>
<td>28−31</td>
<td>VV</td>
<td>6</td>
<td></td>
<td>500</td>
<td>7</td>
<td>FL+ab</td>
</tr>
<tr>
<td>6</td>
<td>2002</td>
<td>Jul</td>
<td>inner shelf</td>
<td>nd</td>
<td>VV</td>
<td>15 RC/5</td>
<td>1</td>
<td>500</td>
<td>3</td>
<td>15 MA</td>
</tr>
<tr>
<td>7</td>
<td>1998</td>
<td>May/Sep</td>
<td>8−22</td>
<td>26−34</td>
<td>SM</td>
<td>30/60</td>
<td></td>
<td>500</td>
<td>3</td>
<td>FL</td>
</tr>
<tr>
<td>8</td>
<td>1995</td>
<td>Sep</td>
<td>~18</td>
<td>32−33</td>
<td>SM</td>
<td>7</td>
<td>3</td>
<td>500</td>
<td>4</td>
<td>FL+ab</td>
</tr>
<tr>
<td>9</td>
<td>1995−2000</td>
<td>spring/fall May/Sep</td>
<td>10−20</td>
<td>28−35</td>
<td>SM</td>
<td>60</td>
<td></td>
<td>500</td>
<td>1</td>
<td>FL+ab</td>
</tr>
<tr>
<td>10</td>
<td>1979−1985</td>
<td>Jun−Jan</td>
<td>11−48</td>
<td>n.d.</td>
<td>SM</td>
<td>44−48/6/2</td>
<td>1−2/5/3</td>
<td>500</td>
<td>8</td>
<td>MA</td>
</tr>
<tr>
<td>11</td>
<td>1976−1977</td>
<td>all seasons</td>
<td>16−51</td>
<td>n.d.</td>
<td>SM</td>
<td>13</td>
<td>4−6</td>
<td>500</td>
<td>9</td>
<td>MA</td>
</tr>
<tr>
<td>12</td>
<td>1989</td>
<td>Jun/Aug</td>
<td>n.d./near shore</td>
<td>n.d.</td>
<td>SM</td>
<td>2</td>
<td>16</td>
<td>500</td>
<td>10</td>
<td>FL+ab</td>
</tr>
<tr>
<td>13</td>
<td>1991</td>
<td>Jun/Aug</td>
<td>n.d./near shore</td>
<td>n.d.</td>
<td>SM</td>
<td>2</td>
<td>16</td>
<td>500</td>
<td>10</td>
<td>FL+ab</td>
</tr>
<tr>
<td>14</td>
<td>2002</td>
<td>summer</td>
<td>15−21</td>
<td>n.d.</td>
<td>VV</td>
<td>23</td>
<td>1</td>
<td>500</td>
<td>3</td>
<td>FL+ab</td>
</tr>
<tr>
<td>15</td>
<td>2002</td>
<td>summer</td>
<td>21−23</td>
<td>n.d.</td>
<td>VV</td>
<td>5</td>
<td>1</td>
<td>500</td>
<td>3</td>
<td>FL+ab</td>
</tr>
<tr>
<td>16</td>
<td>2002</td>
<td>summer</td>
<td>21−24</td>
<td>n.d.</td>
<td>VV</td>
<td>9</td>
<td>1</td>
<td>500</td>
<td>3</td>
<td>FL+ab</td>
</tr>
</tbody>
</table>

See Appendix 3 for literature citations corresponding to the reference numbers (Ref. #) given above, and Appendix 12 for the group or person responsible for species/taxon identifications (see
corresponding ID # for each study). Although not listed above the 1993/1994 REMAP dataset for the NY/NJ Harbor system, and the 2005/2006 NCA were indirectly incorporated into the species/taxon list (Appendix 11).

3.2 Expert survey/tolerance group assignments

Five of the 13 experts solicited, participated in the species/taxon survey in addition to the group at IMCS; however, one survey was incomplete and could not be included (see Appendix 10, expert surveys with tolerance group assignments and comments). Frequency distributions of the number species/taxa assigned to tolerance groups I–V were generally variable among experts; however, all experts considered the majority of species/taxa to be sensitive to organic enrichment (tolerance groups I and II), (Fig. 2). There was no agreement among experts for 34% of species/taxa (69/203 species/taxa), where three or four different tolerance groups were assigned to a single species/taxa (Fig. 3). There was general agreement among experts for 66% of species/taxa (134/203 species/taxa), where all five, four, and three experts assigned the same tolerance group for 1 species/taxon (0.5% of total), 24 species/taxa (12% of total), or 109 species/taxa (54%), respectively (Fig. 3). Following the review of expert assignments by the IMCS committee and the assignment of tolerance groups to 18 additional species/taxa, tolerance groups were determined for a total of 218 species/taxa (see Appendix 9). Figure 4A, B summarizes these results. The majority of species/taxa (81%; 177/218 species/taxa) were considered sensitive to organic enrichment (tolerance groups I and II), whereas relatively more tolerant species/taxa belonging to groups III, IV and V made up 16% (34 species/taxa), 3% (6 species/taxa) and 0%, respectively.
Figure 2 Frequency distribution of number of species/taxa ($n = 203$) assigned to tolerance groups I–V by each expert.
Figure 3 Percentage of species/taxa for which there is disagreement and agreement among five experts for tolerance group assignments of species/taxa on NJ list (n = 203). Inset indicates which tolerance groups were most often agreed upon. Colors in pie chart correspond with colors in the Table.
Figure 4 A. Frequency distribution of number of species/taxa; B. Percentage of species/taxa assigned to tolerance groups I–V based on results from all experts combined ($n = 218$). None was assigned to group V.
3.3 Community measures 2007 and 2009 (based on 500-µm mesh sieve datasets)

A total of 43,182 individuals belonging to 239 species/taxa were collected in grab samples taken at stations in NJ coastal waters in 2007 (n = 100; total area sampled 4 m²). Although only half the number of stations were sampled in 2009 (n = 53; total area sampled 2.1 m²) the total abundance of benthic fauna was much higher (70,033 individuals) than in 2007, whereas, the total number of species/taxa sampled was lower (186 species/taxa). The ten numerically dominant species/taxa in 2007 included the following: the polychaetes Polygordius spp. (1), Prionospio pygmaeus (2), Tharyx sp. A (5), and Aricidea catherinae (7); the oligochaetes Naidinae sp. 2 (3), Grania longiducta (4), Peosidrilus coeloprostatus (8), and Tubificoides sp. 1(10); the amphipod Protohaustorius deichmannae (6); and the bivalve Nucula proxima (9), (number in parenthesis indicates descending order of abundance). The same species/taxa dominated assemblages in 2009 (order of abundance not provided) with the exception of P. pygmaeus, P. coeloprostatus, and Naidinae sp. 2 which were replaced among the top ten by two capitellid polychaetes, Amastigos caperatus (5) and Mediomastus ambiseta (6), and the bivalve Angulus agilis (9). Appendices 13−14 show the total number of individuals, and mean densities (no. individuals 0.04 m²), with standard deviations and 95% confidence intervals for each taxon over all sampling stations in 2007 and 2009, respectively. Only a single individual was found for 13% of the taxa (34/239) in 2007, and 17% of taxa in (32/186) in 2009. The higher density of fauna in 2009 was partly due to elevated densities of a single taxon, Polygordius spp., which made up 34% of the macrofaunal density (\( \bar{x} = 148 \pm 87 \) CI ind. 0.04 m²) at stations sampled in 2007 (range: 0–2603 ind. 0.04 m²) compared to 70% (\( \bar{x} = 927 \pm 598 \) CI ind. 0.04 m²) in 2009 (range 0–10 942 ind. 0.04 m²), (see Appendices 13−15 ). Density of Polygordius spp. was significantly (p<0.0001; \( \alpha = 0.05 \); Mann U = 1658) higher in 2009 compared to 2007. Total abundance excluding Polygordius spp., however, was still relatively higher at stations sampled in 2009 (\( \bar{x} = 392 \pm 137 \) CI ind. 0.04 m²; range: 26–3213 ind. 0.04 m²) compared to 2007 (\( \bar{x} = 283 \) ind. 0.04 m²).
Even though fewer species/taxa were sampled in 2009, species richness among stations was not significantly different between the two years (2007: $\bar{x} = 25 \pm 1.7$ CI taxa 0.04 m$^{-2}$; range: 4–44 taxa 0.04 m$^{-2}$; 2009: $\bar{x} = 25 \pm 2.4$ CI ind. 0.04 m$^{-2}$; range: 9–46 ind. 0.04 m$^{-2}$) (Fig. 6; Appendices 15 and 16). Taxon diversity (Mann U = 1787.0) and evenness (Mann U = 1778.0) were significantly (p = 0.001; $\alpha = 0.05$) higher in 2007 ($H'\bar{x} = 2.2.02 \pm 0.11, J'\bar{x} = 0.64 \pm 0.03$) compared to 2009 ($H'\bar{x} = 1.64 \pm 0.18, J'\bar{x} = 0.52 \pm 0.06$) (Appendices 16–19).

There were 71 species in 2007 that were not sampled in 2009, and 23 species in 2009 that were not sampled in 2007. The majority of these species were rare, and present at very low densities (<10 ind. 0.04 m$^{-2}$). Exceptions to this included 13 species that were only sampled in 2007 (Table 3), as well as two species only sampled in 2009 including the oligochaete *Limnodriloides medioporus*, and the amphipod *Melita nitida* made up 38% (20/53 stations; max density: 115 ind. 0.04 m$^{-2}$), and 4% (2/53 stations; max density: 83 ind. 0.04 m$^{-2}$) of stations, respectively. Hurlbert-Sanders rarefaction curves comparing species/taxon richness across all samples taken in 2007, 2009, and combined for both years are shown in Figure 7. These results also indicate that stations sampled in 2009 had a lower overall diversity in comparison to those sampled in 2007. None of the curves leveled off at a fixed number of species/taxa indicating that diversity might increase with additional sampling. There were no visible trends in any of these community measures in relation to summer upwelling nodes (areas along the coast that may experience hypoxic conditions (Glenn et al., 2004), distance from an outfall, or with position (north to south) along the coast) (Fig. 5 and 6; Appendices 15, 18–19). Statistical analysis showed that species/taxon evenness and diversity were the only community measures that significantly differed between upwelling and non-upwelling nodes in 2007 and 2009, respectively. In 2007 species/taxon evenness was significantly higher at upwelling nodes
(\bar{x} = 0.67 \pm 0.04) compared to non-upwelling nodes (\bar{x} = 0.60 \pm 0.05) (p = 0.41; \alpha = 0.05; Mann U = 950.0), and in diversity was significantly higher at upwelling nodes (\bar{x} = 1.81 \pm 0.27) compared to non-upwelling nodes (\bar{x} = 1.46 \pm 0.24) in 2009 (p = 0.034; \alpha = 0.05; Mann U = 232.0). Total density and richness of benthic macrofauna were significantly (p < 0.0001), correlated with water depth in both years (2007: density r = 0.56 [excluding Polygordius spp. r = 0.40] / richness r = 0.59; 2009: density r = 0.71 [excluding Polygordius spp. r = 0.28] / richness r = 0.62).

Table 3 Species identified in samples taken in 2007 not present in 2009 samples. For each species the corresponding major taxonomic group, maximum density (No. ind. 0.04 m\(^{-2}\)) at any station, number of stations present/sampled, and total abundance across all stations sampled are provided. Species listed alphabetically by group and species.

<table>
<thead>
<tr>
<th>Group</th>
<th>Species</th>
<th>Max. density</th>
<th>No. of stations present</th>
<th>Total abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amphipoda</td>
<td><em>Acanthohaustorius intermedius</em></td>
<td>23</td>
<td>2</td>
<td>24</td>
</tr>
<tr>
<td>Amphipoda</td>
<td><em>Cerapus tubularis</em></td>
<td>27</td>
<td>7</td>
<td>34</td>
</tr>
<tr>
<td>Amphipoda</td>
<td><em>Elasmopus levis</em></td>
<td>16</td>
<td>4</td>
<td>37</td>
</tr>
<tr>
<td>Amphipoda</td>
<td><em>Monocorophium tuberculatum</em></td>
<td>12</td>
<td>4</td>
<td>31</td>
</tr>
<tr>
<td>Decapoda</td>
<td><em>Heteromysis formosa</em></td>
<td>12</td>
<td>9</td>
<td>29</td>
</tr>
<tr>
<td>Decapoda</td>
<td><em>Hexapanopeus angustifrons</em></td>
<td>15</td>
<td>4</td>
<td>22</td>
</tr>
<tr>
<td>Gastropoda</td>
<td><em>Crepidula fornicata</em></td>
<td>16</td>
<td>5</td>
<td>22</td>
</tr>
<tr>
<td>Gastropoda</td>
<td><em>Crepidula plana</em></td>
<td>32</td>
<td>5</td>
<td>42</td>
</tr>
<tr>
<td>Polychaeta</td>
<td><em>Carazziella hobsonae</em></td>
<td>11</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>Polychaeta</td>
<td><em>Erinaceusyllis erinaceus</em></td>
<td>56</td>
<td>12</td>
<td>94</td>
</tr>
<tr>
<td>Polychaeta</td>
<td><em>Prionospio steenstrupi</em></td>
<td>45</td>
<td>2</td>
<td>46</td>
</tr>
<tr>
<td>Polychaeta</td>
<td><em>Syllis cornuta</em></td>
<td>18</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>Polychaeta</td>
<td><em>Tharyx acutus</em></td>
<td>22</td>
<td>6</td>
<td>54</td>
</tr>
</tbody>
</table>
Figure 5 Density of benthic fauna excluding *Polygordius* spp. (log number individuals 0.04 m$^{-2}$; retained on a 500-µm sieve) at each station sampled in A. 2007 ($n = 100$; 1 grab station$^{-1}$), and B. 2009 ($n = 53$; 1 grab station$^{-1}$). Stations on x-axis listed in order of their general position along the coast (i.e., north to south), and correspond with numbers in Fig. 1. Dashed line = average (2007: 283 ind 0.04 m$^{-2}$; 2009: 393 ind 0.04 m$^{-2}$); pink bars = stations in upwelling nodes; white bars = stations in non-upwelling regions; * = stations <1000 m from an outfall (in any direction); letters = alternating non-upwelling regions and upwelling nodes north to south along coast (see Fig. 1).
Figure 6 Taxon richness of benthic fauna (retained on a 500-µm sieve) at each station sampled in A. 2007 ($n = 53$; 1 grab station$^{-1}$), and B. 2009 ($n = 100$; 1 grab station$^{-1}$). Stations on x-axis listed in order of their general position along the coast (i.e., north to south), and correspond with numbers in Fig. 1. Dashed line = average; pink bars = stations in upwelling nodes; white bars = stations in non-upwelling regions; * = stations <1000 m from an outfall (in any direction); letters = non-upwelling regions and upwelling nodes north to south along coast (see Fig. 1).
Figure 7 Hurlbert-Sanders rarefaction curves for infaunal community grab samples (0.04 m²) pooled across stations for 2007, 2009, and in both years.

3.4 PCA-H community analysis (based on 500-µm mesh sieve dataset)

PCA-H analysis based on the normalized hypergeometric sample-by-species probability matrix of grab samples taken at stations in coastal NJ waters in 2007 was used to compare variation in community assemblages among stations (n = 100; 1 grab sample station⁻¹; see map Fig. 1). This analysis was also conducted on combined sample-by-species data for 2007/2009, as well separately for 2009 (n = 153 and n = 53, respectively; 1 grab sample station⁻¹; see Fig. 1). Three main figures are used to show each of the pair-wise, two-dimensional projections of the three-dimensional matrix of similarities for each dataset described above. These projections of the data were then interpreted to determine the main environmental factors responsible for differences in community assemblages among stations, and those found to be important included sediment grain size, total sedimentary...
organic carbon, and water depth. In 2007 and 2009 no clear patterns differentiating benthic communities in upwelling nodes compared to non-upwelling regions were observed in any of the three projections (Appendix 20–21). Moreover, stations within 1000 m of an outfall in any direction did not group together independently of environmental parameters examined (Fig. 8A-11A; Appendix 22A–25A). Species vectors (Gabriel Euclidean distance biplot) were overlaid on community ordination to show which species contribute to CNESS variation among samples and therefore influence spatial patterns (details given below).

3.5 Spatial patterns and community structure: PCA-H Axes 1 & 2

The projection of PCA-H Axes 1 and 2 accounted for most of the variation in community composition, and explained 18% and 11% of the variation in 2007 (Appendix 22A–D). The projection of these axes best illustrates the differences in community composition between different sediment types/properties (i.e., grain size and total organic carbon [TOC]), and water depths (Appendix 22A–D). Along Axis 1, samples/stations tended to group together based on sediment grain size with the amount of silt and clay (i.e., <5% or >5%) being important. Samples/stations along Axis 2 tended to group based on total sedimentary organic carbon (<0.35% or >0.35%), as well as water depth. A depth gradient superimposed on stations that primarily grouped by grain size is illustrated in Appendix 22D.

The projection of the PCA axes 1 and 2 for the 2009 infaunal data explained 26% and 12% of the variation in community composition, respectively, and also showed differences in community composition between sediment grain size, and water depth (Appendix 25A). Samples/stations along Axis 1 tended to be arranged based on silt clay content of <2% in the negative direction, and >2%−5% in the positive direction, whereas, relatively higher amounts of silt clay (>5%) were important in organizing samples/stations along Axis 2 (positive direction), (environmental patterns
not illustrated for 2009). In contrast to 2007, samples/stations along Axis 2 did not group based on sedimentary organic carbon (<0.35% or >0.35%). Instead samples/stations with the highest concentrations of sedimentary organic carbon were present in a range of sediment types (<2%, 2–5%, and >5% silt clay).

Principal components analysis of combined 2007/2009 infaunal data produced similar results to those observed for 2007 (see Figure 8A-D and Appendix 22A-D, respectively). However, the grouping of samples/stations based on <5% or >5% silt clay along PCA Axis 1 was less clear for the combined 2007/2009 data. Several samples/stations in 2009 with <5% silt clay content grouped with samples/stations from 2007 having >5% silt clay (Fig. 8B). This result is reasonable given the different distribution in sediment grain size observed along Axis 1 for 2009.

3.6 Community structure: PCA Axes 1 and 2

The taxa most responsible (accounting for 2–5% of the variation) for the separation of samples/stations based on sediment grain size along Axis 1 in 2007 were the polychaetes Polygordius spp., the tanaid Tanaissus psammophilus, Nemertina spp. and the oligochaete Grania longiducta in the negative direction (<5% silt clay, coarser sediments), and two polychaetes Prionospio pygmaeus, Spiophanes bombyx, three amphipods Protohaustorius deichmannae, Acanthohaustorius millsii, and Ampelisca verrilli, two bivalves Angulus agilis and Donax variabilis, and the oligochaete Naidinae sp. 2 in the positive direction (>5% silt clay, finer sediments), (Appendix 22B). The taxa most responsible for the separation based on total sedimentary organic carbon along Axis 2 included Polygordius spp., P. pygmaeus, S. bombyx, A. verrilli, A. agilis, and Naidinae sp. 2 in the positive direction (>0.35% TOC), and T. psammophilus, Nemertina spp., G. longiducta, A. millsii, P. deichmannae, and D. variabilis in the negative direction (<0.35% TOC), (Appendix 22C). Of these taxa Polygordius spp. tended to be more abundant at depths from 14–23
m, whereas *P. deichmannae*, *A. millsi*, and *D. variabilis* were abundant at shallower depths up to 7 m (Appendix 22D). The same species were important in 2007/2009 with the exception of *G. longiducta*, *S. bombyx*, and Naidinae sp. which did not account for 2–5% of CNESS variation in any of the biplots (Fig. 8A, 9A, 10A). Additionally, the polychaete *Tharyx* sp. A, and the oligochaete *Amastigos caperatus* were found to be important along Axes 1 and 2 in the positive direction (>5% silt clay, and >0.35% TOC, respectively), (Fig. 8B-C ). The taxa most responsible for the separation of samples/stations based on sediment grain size along Axis 1 in 2009 included *Polygordius* spp. in the negative direction (<2% silt clay, coarser sediments), and *P. pygmaeus*, *A. agilis*, and *A. caperatus* in the negative direction (>2–5% silt clay, finer sediments), (Appendix 25A). *Protohaustorius deichmannae* was important along Axis 2 (negative direction), and the oligochaete *Tectidrilus gabriellae*, and polychaetes *Tharyx* sp. A, and *Mediomastus ambiseta* were important in the positive direction (>5% silt clay) (Appendix 25A).
Figure 8 PCA-H metric scaling ordination of benthic macrofaunal community spatial patterns for grab samples (0.04 m$^2$) taken at stations ($n = 153$; 1 grab sample station$^{-1}$) in NJ coastal waters in 2007 and 2009 based on CNESS ($n = 15$ individuals). First two axes explain 18% and 10% of variance in the data, respectively. Solid and dashed arrows indicate taxa contributing to 5 and 2% of CNESS variation in biplots, respectively. Taxa in bold indicate those with heavily weighted factor loadings ($\pm 0.5$). (A) sampling stations indicated by numbers (black font = 2007, blue and green font = 2009, bolded black font and green font with corresponding numbers = stations initially sampled in 2007 and resampled/re-visited in 2009, red font = stations <1000 m from an outfall for both years [in any direction], blue font with red box = dumpsite stations 2009) (also see map Fig. 1); plots B and C are the same plot where in B, black = 2007, blue = 2009 but with, (B) filled squares = stations with < 5% silt clay; open squares = > 5% silt clay; (C) filled squares = stations with < 0.35% total organic carbon (TOC), open squares = > 5% TOC; (D) squares with black outline = 2007, squares with colored outline = 2009, red squares = station depth 0–7 m, blue squares = station depth 7–14 m, green square = station depth 14–23 m.

3.7 Spatial patterns and community structure: PCA-H Axes 1 and 3 and 2 and 3

The projection of PCA-H Axes 1 and 3, as well as 2 and 3 for 2007 also indicated the importance of sediment grain size and TOC in influencing community composition, respectively. The projection of Axes 1 and 3 found an additional polychaete *Magelona* sp. was important along Axis 1 in separating communities based on sediment grain size in the positive direction (>5% silt clay), and projection of Axes 2 and 3 found an oligochaete *Heterodrilus arenicolus* that was important along Axis 2 in separating communities based on TOC in the negative direction (<0.35% TOC), (Appendices 23B and 24B, respectively). In 2007 Axis 3 only explained 7% of the variance in community composition, and no clear station groupings or trends/gradients in environmental factors were identified along this axis. This is in contrast to the analysis of combined 2007/2009 data where a temporal trend was observed along Axis 3 mainly for sediments having <5% silt clay and <0.35% TOC with 2007 samples/stations in the positive direction, and 2009 samples/stations in the negative direction (Fig.9B, and 10B). This trend was likely due to the higher abundance of infauna observed in 2009, especially for *Polygordius* spp. In 2009, Axis 3 explained 9% of the variance in community composition, and a depth gradient was evident along Axis 3. In 2009 the projection of PCA-H Axes 2 and 3, had samples/stations arranged along Axis 2 (in the lower right hand quadrant) that
contained an assemblage of species/taxa not present in PCA-H analysis of the 2007 and 2007/2009 data (Fig. 11). This community was dominated by several oligochates (T. gabriellae, Tubificoides sp.1., and G. longiducta), the bivalve N. proxima, and three polychaetes including a cirratulid Tharyx sp., a capitellid M. ambiseta, and a syllid P. longicirrata.
Figure 9 PCA-H metric scaling ordination of benthic macrofaunal community spatial patterns for grab (0.04 m$^2$) samples taken at stations ($n = 153$; 1 grab sample station$^{-1}$) in NJ coastal waters in 2007 and 2009 based on CNESS ($n = 15$ individuals). Axes 1 and 3 explain 18% and 8 of the
variance, respectively. Solid and dashed arrows indicate taxa contributing to 5 and 2% of CNESS variation in biplots, respectively. Taxa in bold indicate those with heavily weighted factor loadings (±0.5). (A) sampling stations indicated by numbers (black font = 2007, blue and green font = 2009, bolded black font and green font with corresponding numbers = stations initially sampled in 2007 and resampled/re-visited in 2009, red font = stations <1000 m from an outfall for both years [in any direction]) (also see map Fig. 1); (B) same plot but black = 2007, blue = 2009 with filled squares = stations with < 5% silt clay, open squares = > 5% silt clay.
Figure 10 PCA-H metric scaling ordination of benthic macrofaunal community spatial patterns for grab samples (0.04 m$^2$) taken at stations ($n = 153$; 1 grab sample station$^{-1}$) in NJ coastal waters in 2007 & 2009.
2007 and 2009 based on CNESS (n = 15 individuals). Axes 2 and 3 explain 10% and 8% of the variance, respectively. Solid and dashed arrows indicate taxa contributing to 5 and 2% of CNESS variation in biplots, respectively. Taxa in bold indicate those with heavily weighted factor loadings (±0.5). (A) sampling stations indicated by numbers (black font = 2007, blue and green font = 2009, bolded black font and green font with corresponding numbers = stations initially sampled in 2007 and resampled/re-visited in 2009, red font = stations <1000 m from an outfall in any direction), (also see map Fig. 1); (B) same plot but black = 2007, blue = 2009 with filled squares = stations with < 0.35% total organic carbon (TOC), open squares = > 5% TOC.

**Figure 11** PCA-H metric scaling ordination of benthic assemblage spatial patterns for grab samples (0.04 m²) taken at stations (n = 53; 1 grab sample station⁻¹) in NJ coastal waters NJ in 2009 based on CNESS (n = 15 individuals). Axes 2 and 3 explain 12% and 9% of the variance, respectively. Solid and dashed arrows indicate taxa contributing to 5 and 2% of CNESS variation in biplots, respectively. Taxa in bold indicate those with heavily weighted factor loadings (±0.5). Sampling stations indicated by numbers ( map Fig. 1). Red font = stations <1000 m from an outfall (in any direction); blue font with red box = former dumpsite stations.

### 3.8 Biotic Index determination and performance

The initial calculation of the biotic index based on 200 potential species/taxa (200 species/taxa resulted from the of 3 larger taxon groups by the IMCS committee, see section 2.3) indicated that the large majority of stations in both years had a biotic index value between 0 (unpolluted), and 2
(slightly polluted), and the distribution of these values among stations was highly variable among experts (Appendix 26A–B). Several species/taxa present at stations in 2007 and 2009 were excluded from the index calculation because they had not been assigned a tolerance group. More than 20% of species/taxa were excluded/unassigned for ~40% of the stations in both years. Moreover, on average 19% and 9% of the total number of individuals were excluded at stations in 2007 (n = 100) and 2009 (n = 53), respectively. This meant that 55% (2007) and 28% (2009) of stations had >10% of the individuals per sample excluded. Based on these results, 18 additional species/taxa were assigned tolerance groups by the IMCS committee, and the index was then recalculated based on 218 potential species/taxa.

Following this modification and recalculation, the average percentage of species/taxa not included in the index calculation was reduced to 6.2% (formerly 19%) and 2.8% (formerly 18%) for 2007 and 2009, respectively. There were no stations in 2009 where >20% of the species/taxa were excluded from the index calculation, and in 2007 the number was greatly reduced (5%; formerly 40%), (stations with >20% species excluded = 1, 3, 61, 68, 99). Furthermore, the average percentage of individuals excluded was 1.9% in 2007 (formerly 19%) and 0.4% in 2009 (formerly 9%). Only 5% of stations in 2007 (formerly 55%) had >10 individuals per sample excluded (stations = 5, 68, 90, 94, 99). In both years index values ranged from 0 to 2 with 28% and 72% of the stations classified as unpolluted (BI = 0 & 1), and slightly polluted (BI = 2), respectively (Fig.12A; Appendices 16–17). The Paul et al. (2001) index also classified 27% and 73% of stations in 2007 as reference and degraded, respectively; however, there was little agreement between the two indices with regard to individual station classifications. For example, only 3 stations were similarly classified as unpolluted (this study) and reference (Paul et al., 2001 index). Using the present study's index 10, 50, and 40% of the stations classified as reference in the REMAP study were determined
to be unpolluted, slightly polluted, and meanly polluted, respectively. In contrast, none of the stations classified as impacted in the REMAP study were considered as reference when the biotic index was applied, with 55 and 45% of impacted stations being classified as slightly or meanly polluted. Moreover, on average 51% of the species/taxa, and 42% of individuals from REMAP stations were excluded from the biotic index calculation.

Biotic indices for the 10 stations sampled in both years of the present study remained the same for 5 stations (BI = 2), increased from an index value of 1 to 2 at two stations, and decreased from 2 to 1 at three stations (Fig. 12B). Fifteen stations, sampled in either 2007 or 2009 during the present study, were assigned an index value (0 to 7) by experts based on species/taxon composition, community measures, and environmental parameters (environmental data provided in Appendices 27–30). There was moderate agreement among expert assignments (67%; values of 0 and 1 were considered to be the same assignment since they both indicate unpolluted conditions). Classifications based on the summarized expert values (determined by majority agreement among assignments) agreed with the calculated biotic index for 60% of the stations examined. For those assignments that were not in agreement (6 stations), 67% of the time (4 stations out of 6) experts provided a value that was one step higher (+1) than the calculated one (i.e., 2 (expert) vs. 1 (calculated)).

Biotic coefficients used to determine the discrete biotic index value (0 to 7) were significantly and positively correlated with water depth, species/taxon richness, and density of Polygordius spp. in 2007 and 2009 following the p-value adjustment for multiple comparisons (Table 4). Considering the unadjusted p-values, TOC was also significantly and positively correlated with index values, whereas, dissolved oxygen, and pH were significantly and negatively correlated (Table 4). Plots of biotic indices with means and 95% confidence intervals for significantly correlated parameters are shown in Fig. 13. Results obtained by comparing mean values for significantly correlated
environmental factors, and community measures for samples having the same biotic index indicated several trends that were consistent between years. A progressive decrease was observed for dissolved oxygen and pH with increasing biotic index values, whereas a progressive increase was observed for depth, TOC, species/taxon richness, and density of Polygordius spp.
Figure 12  A. Frequency distribution indicating number and percentage of stations in 2007 and 2009 with biotic indices 0–7 based on finalized summary of species tolerance groups supplied by experts, B. biotic indices for 10 stations sampled in both years.
Table 4  Spearman rank correlation of environmental variables and community measures with biotic coefficients for 2007 stations \((n = 100)\) and 2009 \((n = 53)\). Significant correlations indicated with bold font for unadjusted and adjusted p-values (initial \(\alpha = 0.05\)). n.d. = no data; only significant correlations are reported.

<table>
<thead>
<tr>
<th>Environmental variables</th>
<th>Biotic coefficient (BC) 2007</th>
<th>Biotic coefficient (BC) 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( r ) unadjusted p-value</td>
<td>( r ) adjusted p-value</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>0.544 (&lt;0.0001)</td>
<td>0.0042 (0.0045)</td>
</tr>
<tr>
<td>Chl (a)</td>
<td>-0.497 (&lt;0.0001)</td>
<td>0.0045 (0.0045)</td>
</tr>
<tr>
<td>Dissolved oxygen (mg L(^{-1}))</td>
<td>-0.248 (0.0130)</td>
<td>0.0056 (0.0071)</td>
</tr>
<tr>
<td>Silt clay%</td>
<td>-0.231 (0.0209)</td>
<td>0.0063</td>
</tr>
<tr>
<td>Sand %</td>
<td>0.231 (0.0209)</td>
<td>0.0071</td>
</tr>
<tr>
<td>Total organic carbon (%)</td>
<td>0.222 (0.0267)</td>
<td>0.0083</td>
</tr>
<tr>
<td>pH</td>
<td>-0.220 (0.0275)</td>
<td>0.0100</td>
</tr>
<tr>
<td>Community measures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Richness (No. taxa/species 0.04 m(^2))</td>
<td>0.421 (&lt;0.0001)</td>
<td>0.0050</td>
</tr>
<tr>
<td>Density (P).(olygordius) spp. (No. ind. 0.04 m(^2))</td>
<td>0.382 (&lt;0.0001)</td>
<td>0.0038</td>
</tr>
<tr>
<td>Shannon diversity H</td>
<td>0.198 (0.0487)</td>
<td>0.0125</td>
</tr>
<tr>
<td>Density excluding (P).(olygordius) sp. (No. ind. 0.04 m(^2))</td>
<td>0.333 (0.0149)</td>
<td>0.0083</td>
</tr>
</tbody>
</table>
Figure 13  Mean ±95% confidence intervals for environmental parameters and community measures (A) depth, (B) dissolved oxygen mg l⁻¹, (C) total organic carbon (%), (D) pH, (E) richness (%), and (F) density Polygordius spp. taken at stations in 2007 (n = 100) and 2009 (n = 53) and associated biotic index values. Note scale on y-axis differs among panels; (F) = log base 10.
4.0 DISCUSSION

This project was conducted in response to the declaration by the state of New Jersey that 100% of its coastal waters were impaired due to hypoxia based on point-in-time sampling by Region 2’s coastal monitoring program using a dissolved oxygen criterion of 5 mg L$^{-1}$ (Balthis et al., 2009), which did not provide any information in regard to biological effects or impacts. Moreover, using dissolved oxygen as a criterion in NJ coastal waters is likely to be misleading since there are four upwelling nodes along the coast. Summer upwellings are generated by sustained winds from the southwest, and they may or may not result in phytoplankton blooms and low water column dissolved oxygen depending on several factors, including the intensity and duration of the winds (Glenn et al. 2004). The need for a biologically meaningful measure of ecological quality using a biotic, rather than a chemical indicator of ecological status for future assessments was recognized. In the present study, complementary environmental and biological data permitted an integrative approach to index development and assessment of the ecological status of benthic communities. Results based on community measures and multivariate analyses of macrofaunal species composition and abundance did not support the declaration of 100% impairment of New Jersey's nearshore ocean waters in 2007 and 2009.

Macrofaunal communities were similar to those found at Beach Haven ridge (LEO-15 research area) off southern New Jersey (Table 5), where stations were set up in the mid-1990's to characterize the sediments and associated macrofaunal communities with the aim of detecting long-term community changes on the inner-shelf. Benthic communities in the present study (2007 and 2009) had a relatively high number of species including a large number of rare species, and species sensitive to organic enrichment. These findings are contrary to what one might expect for impaired communities. Highly impaired communities, relative to unpolluted areas considered to represent
reference/natural conditions, often contain a reduced number of species with low evenness resulting from the loss of rarer and more sensitive species, and subsequent prevalence of more tolerant ones (Pearson and Rosenberg, 1978). Based on the ecological/tolerance groups assigned to species/taxa by experts in the present study, benthic communities did not contain a high proportion of the opportunistic species typically found in organically enriched and muddy sediments associated with low redox potential and hypoxia (Pearson and Rosenberg, 1978; Hyland et al., 2005). Moreover, patterns in species composition, distribution, and abundance were primarily influenced by natural sources of environmental variation (i.e., depth, sediment type, and "natural " levels of total organic carbon), rather than by pollution-related surrogates such as dissolved oxygen and "unnatural" levels of organic carbon consistent with organic enrichment. Multivariate analyses did, however, reveal some noteworthy spatial patterns that may indicate that a small subset of stations sampled may be showing initial signs of degradation, and therefore should be monitored in future assessments (discussed in below).

Initial application of the biotic index (modified from Borja et al., 2000) indicated that 28% percent of stations sampled over both years were considered unpolluted (BI = 0 & 1), containing a relatively high proportion of species/taxa that are sensitive to organic enrichment representing a "normal or impoverished" community (Borja et al., 2000). The remaining 74% of stations also had a relatively high ecological status, classified as being slightly polluted (BI = 2). These communities contained a high proportion of species/taxa that are relatively tolerant to organic enrichment but are also known to occur under "normal" conditions (Borja et al., 2000). Moreover, the water column dissolved oxygen criterion of 5 mg L$^{-1}$, which was used in the assessment that reported 100% of New Jersey's ocean waters to be impaired due to hypoxia, is above the concentration expected to have a severe impact on benthic communities, and the present study confirms this. Diaz and
Rosenberg (1995) reported that benthic infaunal mortality can be initiated when oxygen concentrations are <2 mg L\(^{-1}\) and more recently, Ritter and Montagna (1999) have proposed that 3 mg L\(^{-1}\) defines the line between normoxic and hypoxic benthic conditions. In the present study, bottom water column dissolved oxygen levels were not <2 mg L\(^{-1}\). Concentrations in 2007 were well above these suggested critical values (\(\bar{x} = 6.2\) mg L\(^{-1}\) ±0.24 CI), while concentrations were lower in 2009 (\(\bar{x} = 4.9\) mg L\(^{-1}\) ±0.45 CI) with 10 stations <3 mg L\(^{-1}\) (\(\bar{x} = 2.6\) mg L\(^{-1}\) ±0.17 CI), (Appendix). Although results of benthic community condition obtained by applying the biotic index were in general agreement with those provided by community analyses, the main findings of this study are primarily based on the latter. Significant progress was made in developing a benthic index for the New Jersey coastal ocean with very positive findings related to its performance; however, results should be interpreted with caution until the index is further calibrated and properly validated (discussed in detail below). Development and application of the AMBI index on which the index in the present study is based have been ongoing since 2000 (Borja et al., 2000; Borja et al., 2003; Borja et al., 2004; Borja and Muxika, 2005; Muxika et al., 2005; Muxika et al., 2007; Van Hoey et al., 2010).

Several of the numerically dominant species in the present study were also among the top ten dominant species at LEO-15 (Grassle et al., 2009), and at comparable areas sampled on the Mid-Atlantic Bight/New York Bight (MAB/NYB) inshore shelf (Boesch et al., 1979; Reid et al., 1991; Burlas, 2001; Valente, 2006), (Table 5). With a relatively large area sampled no single species/taxon was present at all stations. The three most common and widespread species/taxa included two bivalves *Spisula solidissima* and *Angulus agilis* (formerly *Tellina agilis*), and the interstitial polychaete *Polygordius* spp. (most likely represents a single species, Ramey et al. 2006) which were found at 69, 71, and 84% of stations, respectively, over both years. All three of these
species are considered to be sensitive to organic enrichment. *Spisula solidissima* is very sensitive, belonging to ecological/tolerance group I, whereas the other two species/taxa are considered to be sensitive/indifferent to organic enrichment (tolerance group II). A large number of rare species/taxa were also found. Consistent with the LEO-15 study, 35% of species/taxa occurred at a single station (Grassle et al., 2009). Rarefaction curves indicated that species richness was higher in the present study (106 and 60 species/taxa · 1000−1 individuals in 2007 and 2009, respectively) compared to communities at LEO-15 sampled at a similar time of year (September: 45 50 and 30 species/taxa · 1000−1 individuals in sand [sta. 9, 30] and muddy-sand [sta. 32], respectively). Higher species richness in the present study is likely a result of the comparatively wider range of depths and sediment types sampled (0−50 m vs. 12−16 m at LEO-15). Species evenness was also slightly higher (2007: $J' \bar{x} = 0.64 \pm 0.03$ CI; 2009: $J' \bar{x} = 0.52 \pm 0.06$ CI) compared to LEO-15 communities (September: 0.47 ±0.04 CI). Multivariate PCA-H revealed that community structure was influenced by depth, sediment type, and "natural " levels of total organic carbon, rather than by pollution-related surrogates (i.e., dissolved oxygen and "unnatural" levels of total organic carbon consistent with organic enrichment). These findings are consistent with non-impaired community conditions.

Multivariate analyses, however, also revealed some spatial patterns that should be monitored in future assessments, and that warrant further discussion. In 2009, 14 stations with <5% silt clay content grouped with stations from 2007 having >5% silt clay (Fig. 8B-C). This means that community composition at these 2009 stations with relatively coarser sediments (<5% silt clay) were more similar to communities typically found in finer sediments with >5% silt clay in 2007. This trend is likely due to similar levels of TOC found in these relatively coarse and fine sediments (2009 <5% silt clay TOC = 0.63% ± 0.23 CI vs. 2007 >5% silt clay TOC = 0.78% ±0.12 CI). This is somewhat unexpected, since coarser sediments with <5% silt clay in 2007 and at other 2009 stations
contained relatively lower concentrations of TOC (0.50 ± 0.11 CI and 0.41% ± 0.05 CI, respectively). Seven of these 14 stations were located just outside the 100-m mixing zone around discharges (Sta. No. 107, 120, 126, 135–137, 142), and when only these stations are considered, sedimentary TOC content was slightly elevated (0.84% ± 0.39 CI) above values observed for sediments with <5% silt clay in 2007 and 2009. The other 7 stations were associated with either non-upwelling regions (Sta. No. 73, 116, 130, 128) or upwelling nodes along the coast (Sta. No. 104, 118, 122). In the PCA-H this group of stations also included five stations located <1000 m from discharges in 2007 and 2009 with >5% siltclay (Sta. No. 47, 68, 76, 98, 143), (Fig. 8B). Only station 135 had a dissolved oxygen value <3 mg L⁻¹. Species richness and diversity at these stations, however, were not reduced and community composition was similar to other coastal stations with relatively high levels of silt clay (2−5%) which were not directly associated with outfall discharges (>1000 m away). Biotic indices indicated that communities at the majority of these stations (71%; 10/14 stations) were either "normal" or "impoverished" (indices of 0 or 1, respectively), and thus were considered to have an unpolluted status.

The projection of PCA-H Axes 2 and 3 for 2009 indicated that stations arranged along Axis 2 in the lower right hand quadrant contained an assemblage of species/taxa not present in PCA-H analysis of the 2007 and 2007/2009 data (Fig. 11). This community was dominated by several oligochaetes belonging to tolerance/ecological group III (*T. gabiellae, Tubificoides* sp.1., and *G. longiducta*), the bivalve *N. proxima* (II), and three polychaetes including a cirratulid *Tharyx* sp. (III), a capitellid *M. ambiseta* (III), and a syllid *P. longicirrata* (II). This assemblage (with varying densities of constituent species among stations) was particularly prominent at six stations including three stations just outside an outfall mixing zone (Sta. No 138–139, 143), one station from the 6-Mile Dumpsite (Sta. No. 131), and two stations (Sta. No. 95 and 129) in an upwelling node on the
southern portion of the coast with relatively fine silt-clay sediments. Sediments at all of these stations, with a single exception (Sta. 95), had the highest concentrations of sedimentary TOC found in both years (TOC = 3.2 ±1.25 CI; 1.9−5.7%), and two stations had dissolved oxygen levels <3 mg L$^{-1}$ (Sta. 138 [DO 2.53 mg L$^{-1}$], 139 [2.13 DO 53 mg L$^{-1}$]). Moreover, during sample collection and onboard processing, station 129 was described by researchers as having muddy, black sediment that smelled of hydrogen sulfide. The sediment surface had no visible signs of biological activity. The biotic coefficient value for this station was the highest observed (3.05), just below the cut-off (>3.3) used by Borja et al. (2000) to indicate a that a community is "transitional to pollution". Based on community measures and environmental parameters the majority of experts also determined this station to be moderately polluted (biotic index = 3). Species/taxon richness, however, at three of these stations (Sta. 138–139, 95) was among the highest observed in 2009, whereas, the other three stations had values just below or above the average (Fig. 6). Species richness has been found to peak at low to slightly moderate levels of TOC, and sediment organic matter provides food for deposit-feeding species, but these TOC levels do not result in oxygen depletion or the build-up of toxic by-products (ammonia and hydrogen sulfide) associated with the breakdown of these materials (Hyland et al., 2005). Biotic indices indicated that benthic communities at all of these stations were unbalanced, having a high proportion of species/taxa belonging to tolerance/ecological group III, and therefore ecological quality was determined to be slightly polluted. These stations may have been showing initial indications of slight degradation.

Significant progress was made in developing a biotic index for coastal New Jersey waters; however, it is important to recognize that to date the index is based on a prevalence of samples from generally unimpaired areas. If this index is to be used to quantitatively assess the ecological status of New Jersey's coastal marine waters it needs to be tested/specifically calibrated using samples from
moderately and heavily impacted locations. To be useful an index should identify or discriminate between a wide range of impacted/degraded and reference/non-degraded/reference ecological conditions. Indices formulated on ecological principles and properly validated will better communicate the complexity of ecological integrity (Borja and Dauer, 2008). Moreover, a system is required that provides a framework that allows for the index to be easily calculated, and that facilitates the incorporation of continuously updated species information.

Index validation is usually accomplished by testing/comparing an index assessment for an area against an independent dataset, i.e., different from the one used to create it (calibration dataset). In an effort to do this, an additional 100 stations were sampled in NJ coastal waters in 2010 but were never sorted and identified for community analyses and index development. Most of these samples were taken from randomly selected stations; however, six samples targeted potentially impacted areas within outfall mixing zones (the area within 100 m of an outfall effluent discharge in any direction) at several discharge locations, in an effort to sample an impaired community. It is recommended that the six samples taken near discharges, and a subset of the randomly sampled stations (n = 50) in 2010, together with future sampling of a modest number of additional samples near discharges (e.g., n = 20) are used for further index development. Specifically, these additional samples would 1) provide information generally lacking on species composition, distribution and abundance patterns of benthic macrofauna inhabiting potentially impacted coastal areas in New Jersey, which could be used to assign and evaluate species tolerance designations; 2) determine the sensitivity/ability of the index in detecting a wider range/continuum of ecological conditions; 3) statistically analyze relationships among a wider range of biotic indices (currently BI = 0−2,) and over a wider range of environmental parameters/community measures; 4) provide a test dataset to determine if the index is able to differentiate impacted/degraded stations from reference/non-
degraded stations to validate it; and 5) assess the thresholds currently being used to determine benthic community health and ecological status. The thresholds currently being applied are based on those developed for Basque Country estuaries in Northern Spain (Table 1; Borja et al., 2000). These thresholds may need to be modified once information is available for benthic communities inhabiting impacted/degraded areas for coastal New Jersey, and in relation to the possible range of biotic indices obtained. In the development and application of the Borja et al. (2000) AMBI index, now used for the assessment of 'ecological status' under the European Water Framework Directive, the initial 7 categories of community health and ecological status were reduced to 5 (Borja, 2004; Borja et al., 2004). A more detailed discussion of these topics in light of the current study results is given below.

Although attempts were made to incorporate data on species composition and abundance from impacted locations at the project's outset by using data from previous studies, and in 2009 by taking samples from the former 6 and 12-Mile Dumpsites, as well as from areas just outside the mixing zones (~100 m away from an outfall discharge in any direction), many of these stations did not exhibit signs of moderate to heavy impairment. For example, community composition at three of the former dumpsite stations was not impaired, and a high density of *Polygordius* spp., a relatively sensitive taxon, known to respond to changes in sediment grain size and sedimentary organic carbon (Ramey and Bodnar, 2008; Grassle et al., 2009) was present. Researchers also noted during sample collection/onboard processing that the former dumpsite stations did not appear to be impaired. The sediment had no smell or visible anoxic layer, and during sieving numerous polychaetes and small crustaceans (amphipods) were observed. As a result only a few species/taxa were found and assigned to tolerance groups IV, and none to group V, and it still remains to be determined how this might affect the sensitivity/ability of the index in detecting moderately to heavily impaired communities.
Tolerance groups were assigned to a total of 218 benthic macrofaunal species/taxa out of the 540 that were known to occur along the New Jersey coast. Of these, 81% (177/218 species/taxa) were considered sensitive or indifferent to organic enrichment (tolerance groups I and II, respectively), 16% (34 species/taxa) were tolerant but also present under "natural conditions" (III), and 3% (6 species/taxa) were second order opportunistic species (IV). No species were determined to be first order opportunistic species (V). Considerable variability was found among expert assignments, where three or four different tolerance groups were sometimes assigned to a single species/taxon (34% of species/taxa). This was not unexpected since tolerance group assignments provided by experts were based on different criteria including personal experience (field and laboratory), published literature, knowledge of a higher taxon group such as Class or Family, or were considered to be “guesses”. Such variability is a reflection of the limited knowledge available for individual species in regard to their responses to natural and or anthropogenic stress/organic enrichment. This is especially true for species inhabiting highly mobile sandy sediments subject to high levels of "natural disturbance" through frequent sediment re-suspension and ripple migration. Several experts commented on the difficulty of this task, pointing to a lack of knowledge as the main contributor to the uncertainty in their assignments. The IMCS committee of experts played an important, constructive role in this process especially with respect to determining assignments for species where there was no agreement. Although some uncertainty remains, assignments are representative of the current state of knowledge.

There are a number of considerations to be aware of when applying this biotic index. The validity of each species identification in the dataset and of the species assigned to tolerance groups must be brought up to date in ITIS or WoRMs prior to index calculation. Moreover, the sensitivity of the index can be reduced when a low number of taxa (1−3) and or individuals (<3) are found in a
sample. If the percentage of unassigned species is high (>20%), Borja and Muxika (2005) caution that index values can be difficult to interpret, and should be evaluated very carefully. If the percentage of unassigned species is >50%, the index should not be used (Borja and Muxika, 2005). Species not assigned to a tolerance group in Borja et al. (2000) had a mean abundance of 1.4%, and often made up <5-10% of the individuals per sample (Borja and Muxika, 2005). In order to follow these recommendations in the present study, tolerance groups were assigned to 18 additional species/taxa found to be notably abundant in coastal New Jersey waters in 2007 and 2009. Following this, only 5% of stations in 2007 and no stations in 2009 had >20% of the species/taxa excluded from the index calculation. The average percentage of individuals excluded was 1.9% and 0.4% in 2007 and 2009, respectively, with only 5% of stations in 2007 with >10 individuals per sample excluded. Each time the index is calculated, the percentage of species and individuals that are excluded should be determined and reported. Due to logistics, over half of the benthic macrofaunal species reported over the years from coastal New Jersey waters remain unassigned to tolerance groups. Although the currently assigned species were suitable for the calculation of the index for the two years examined, species not considered necessary for inclusion could become more abundant over time making them a necessary part of the index calculation. Considerable temporal differences in species composition and abundance have been shown to occur at LEO-15 (Grassle et al., 2009). Thus, tolerance values need to be assigned to a greater number of species. In a five-year period more than 900 species were assigned tolerance groups by Borja et al. (2000), and the list created for Europe now contains ~5,900 species/taxa (http://ambi.azti.es/). A more complete list of species tolerance assignments will make the index more comprehensive for future assessments. A system or software should be developed that provides a framework that allows for the index to be easily calculated, and that facilitates the incorporation of continuously updated species information.
that is similar to the one produced for the AMBI (see http://ambi.azti.es/; Borja et al., 2000). If such software is made available online it has the potential to be widely used by the scientific community working in the NJ coastal ocean, and provides an open forum for researchers to make suggested updates to species/taxa (e.g., taxonomy, tolerance assignments, etc.), to aid in keeping the index up-to-date with current information. In the present study identifications of a few species/taxa namely *Polygordius* spp. (likely a single species, see Ramey et al., 2006), *N. proxima* (may be confused with *N. annulata*, see Grassle et al., 2009), and *Tharyx* sp. A (is it an undescribed species?) should be confirmed by experts.

Encouraging results were obtained in regard to assessment of index performance. The biotic indices ranging from 0−2 (note restricted range) were significantly correlated with pollution-related surrogates in the expected direction indicating that these factors were indeed incorporated indirectly using species' tolerances. For instance, the index increased with increasing sedimentary organic carbon and water depth, and decreased with increasing dissolved oxygen concentration and pH. It was also positively correlated with species/taxon richness and density of *Polygordius* spp. which is a reasonable finding for the low levels of total organic carbon (Hyland et al., 2005; Ramey and Bodnar, 2008; Ramey et al., 2009) measured in the present study. This correlation is expected to disappear as at higher biotic index values, and relatively higher concentrations of sedimentary organic carbon. Index performance was also addressed by examining the level of agreement between the calculated biotic indices, and the same series of values assigned by the IMCS committee of experts for 15 stations selected from the 2007 and 2009 surveys. Assignments were based on selected environmental parameters and community measures. There was 67% agreement among expert assignments of an index value (0 to 7) and classifications based on the summarized expert values (determined by majority agreement among assignments) agreed with the calculated biotic
index for 60% of the stations examined. Index performance based on the level of agreement of results between the biotic index of the present study, and other biotic metrics were determined to be inappropriate due to the different scales of classification employed (i.e., biotic index = 7 levels and Paul et al. (2001) and REMAP indices only had 2 levels). Moreover, a high proportion of species/taxa and individuals in the REMAP study were excluded from the calculation because tolerance groups had not been assigned. Thus, even though REMAP stations selected were within the depth, salinity and grain size ranges specified in the present study macrofaunal species composition was very different in NJ estuaries.

Finally, the index should not be applied automatically. A more detailed analysis and discussion of results by experts should always be an integral part of assessments (Borja and Muxika, 2005). Although the main aim of the index is to summarize the complex environmental and community data used to determine ecological quality into a single number that can be understood by the public, media, resource users, and the decision makers in management actions, this does not negate the need for more integrated and detailed analyses of the data. The index should be used in conjunction with other univariate and multivariate community analyses as in the present study, especially at the early stages of index development and application. This can aid in reducing potential misclassifications in the assessment of ecological status, and allows for a more accurate and comprehensive assessment (Borja et al., 2004; Borja and Muxika, 2005). This is especially important in areas where the effects on benthic communities of both natural and anthropogenic stresses are relatively poorly understood.
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Page 69 of 70


