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Review

Ecological condition of US Mid-Atlantic estuaries, 1997–1998

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Abstract

The Mid-Atlantic Integrated Assessment (MAIA-Estuaries) evaluated ecological conditions in US Mid-Atlantic estuaries during the summers of 1997 and 1998. Over 800 probability-based stations were monitored in four main estuarine systems—Chesapeake Bay, the Delaware Estuary, Maryland and Virginian coastal bays, and the Albemarle–Pamlico Estuarine System. Twelve smaller estuaries within the four main systems were also assessed to establish variance at the local scale. A subset of the MAIA-Estuaries data is used here to estimate the extent of eutrophication, sediment contamination, and benthic degradation in mid-Atlantic estuaries. An Environmental Report Card and Index of Environmental Integrity summarize conditions in individual estuaries, the four estuarine systems, and the entire MAIA region. Roughly 20–50% of the region showed signs of eutrophication (high nutrients, excessive production of organic matter, poor water clarity, or depleted dissolved oxygen), 30% had contaminated sediments, and 37% had degraded benthic communities. Compared with the Environmental Monitoring and Assessment Program (EMAP)-Virginian Province study in 1990–1993, larger fractions of Chesapeake Bay (17%) and Delaware River (32%) had increased metals or organics in sediments. Published by Elsevier Ltd.

Keywords: US Mid-Atlantic estuaries; MAIA-Estuaries; Eutrophication; Sediment contamination; Benthic condition

1. Introduction

In 1972 the US Congress passed the Clean Water Act, largely in response to declining water quality in our nation's surface waters, including estuaries. Subsequently, numerous monitoring and research programs were begun in estuarine systems throughout the country, among them Chesapeake Bay in 1984 (www.chesapeakebay.net/history.htm) and Long Island Sound, Narragansett Bay, Buzzard's Bay, and Puget Sound in 1985 with the initiation of the National Estuary Program (www.epa.gov/owow/estuaries). Despite considerable expenditures, however, neither the US Environmental Protection Agency (EPA) nor any other federal agency could accurately assess the environmental condition of the nation's estuaries, nor could regulators document the nationwide effectiveness of pollution-control legislation (Messer et al., 1991).

In response to these limitations, the EPA began the Environmental Monitoring and Assessment Program (EMAP) in 1990 to monitor the condition and trends of the natural resources of the US and to develop innovative methods for assessing the environment (USEPA, 1990). EMAP-Estuaries monitored the Virginian Biogeographic Province (the Atlantic coast from Cape Cod, MA, to Cape Henry, VA) from 1990 to 1993, the Louisianian Province (Gulf of Mexico north of Tampa Bay) from 1991 to 1994, and the Carolinian Province (southeast Atlantic coast) from 1994 to 1997. A unique feature of these programs was the use of probabilistic designs to select sampling sites that provided unbiased quantitative estimates of ecological condition (Overton et al., 1991). All the EMAP-Estuaries projects used a common core of physical, biological, and chemical indicators that focused on response variables but included exposure and habitat variables (Holland, 1990; Messer et al., 1991; Summers et al., 1995; Hyland et al., 1998; Paul et al., 1999; Strobel et al., 1999).

The uniform regional assessments provided by EMAP-Estuaries had several limitations, however.

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Projects were logistically challenging and expensive for a single agency to administer. There was only minimal collaboration with existing monitoring programs, partly because of EMAP's unique design. And estuaries were grouped in three broad categories (large estuaries, small estuaries, and tidal tributaries) because there were too few stations to assess individual estuaries or tributaries—resources of intense interest to regional and local environmental managers.

In 1994, the Committee on the Environmental and Natural Resources (CENR) evaluated the state of all environmental monitoring and assessment efforts in the US and concluded that although immediate goals were being met, individual programs were largely uncoordinated, limited to a single resource or issue, and yielded incompatible data sets (CENR, 1996). The committee recommended that multiple agencies collaborate and combine resources when assessing the environment, and further urged that all renewable natural resources of a region be assessed in a truly integrated fashion (CENR, 1996). Partly in response to these recommendations, the USEPA Office of Research and Development (ORD) formed a partnership in 1995 with USEPA Region 3 to create a research, monitoring, and assessment program for the mid-Atlantic region of the US (Bradley and Landy, 2000). Federal, state, and local organizations pooled their monitoring programs and expertise to conduct the multiresource assessment, which was called the Mid-Atlantic Integrated Assessment (MAIA). Here we examine the estuarine component of MAIA, called MAIA-Estuaries.

MAIA-Estuaries sampled the Delaware Estuary, Chesapeake Bay, the coastal bays of Maryland and Virginia, and the Albemarle–Pamlico Estuarine System (APES), a total area of 23,100 km², during the summers of 1997 and 1998. It also intensively sampled 12 smaller estuaries within the larger system in order to evaluate local conditions and variability.

MAIA-Estuaries differed from the EMAP estuarine projects in several significant ways. It was a collaboration of several federal agencies, universities, and regional environmental organizations, whereas the early EMAP estuarine studies were administered by a single organization (EPA ORD). The MAIA study incorporated sampling networks of existing monitoring programs wherever possible, whereas EMAP-Estuaries used a systematic grid of stations designed specifically for it. And MAIA-Estuaries measured additional water-quality indicators in order to better evaluate the extent of eutrophication in the estuaries. These changes provided a fuller ecological assessment at a finer spatial resolution.

The primary goals of MAIA-Estuaries were to: (1) acquire the data needed to make sound environmental decisions for mid-Atlantic estuaries; (2) augment the core suite of EMAP indicators with measures of eutrophication; (3) contribute to an integrated assessment

of multiple natural resources in the mid-Atlantic region; (4) communicate the program's results to a broad audience of environmental managers, scientists, and the concerned public; and (5) improve methods for conducting joint environmental assessments.

This manuscript first describes the design, implementation, and analytical methods of MAIA-Estuaries. It then uses 10 indicators to evaluate the extent of eutrophication, sedimental contamination, and impairment to the benthic community in mid-Atlantic estuaries on multiple spatial scales. It makes the results understandable and useful to a broad audience by presenting them in several formats, including a Report Card and an Index of Environmental Integrity (IEI). It concludes by briefly examining evidence for regional environmental change by comparing the results of the MAIA and EMAP-VP estuarine studies conducted half a decade apart. A summary report of the results of MAIA-Estuaries was prepared for a broad audience, including the nontechnical public (USEPA, 2003), and the complete MAIA-Estuaries data set is available online at www.epa.gov/emap/maia/html/data.html.

2. Methods

2.1. Program design

A consortium of federal and state partners planned and executed MAIA-Estuaries. The partners included EPA, the National Oceanic and Atmospheric Administration (NOAA), Chesapeake Bay Program (CBP), the Delaware River Basin Commission, the National Park Service (NPS), the US Fish and Wildlife Service, the National Estuaries programs (in Delaware Estuary, Delaware Inland Bays, Maryland Coastal Bays, and APES), and the states of Delaware, Maryland, North Carolina, Virginia, New Jersey, and Pennsylvania. More than 800 stations were sampled in Chesapeake Bay, the Delaware Estuary, the coastal bays of Maryland and Virginia, and APES (Fig. 1). Twelve estuaries were sampled with greater spatial resolution (5–29 stations each) in order to determine the smaller-scale variability (Fig. 1). The coastal bays in Delaware had been monitored in 1993 (Chaillou et al., 1996), and were not included in MAIA. Sampling stations were incorporated from ongoing monitoring programs in the region as long as they were compatible with the probability-based design (USEPA, 2003). NOAA sampled the Delaware Estuary at sites used by the National Status and Trend (NS&T) Program. The CBP collected samples in Chesapeake Bay at their network of water and sediment stations. (Only the first CBP station visit after August 1 was included in the MAIA-Estuaries database.) The NPS collected samples in Chincoteague Bay. NOAA and the University of North Carolina sampled at NS&T stations

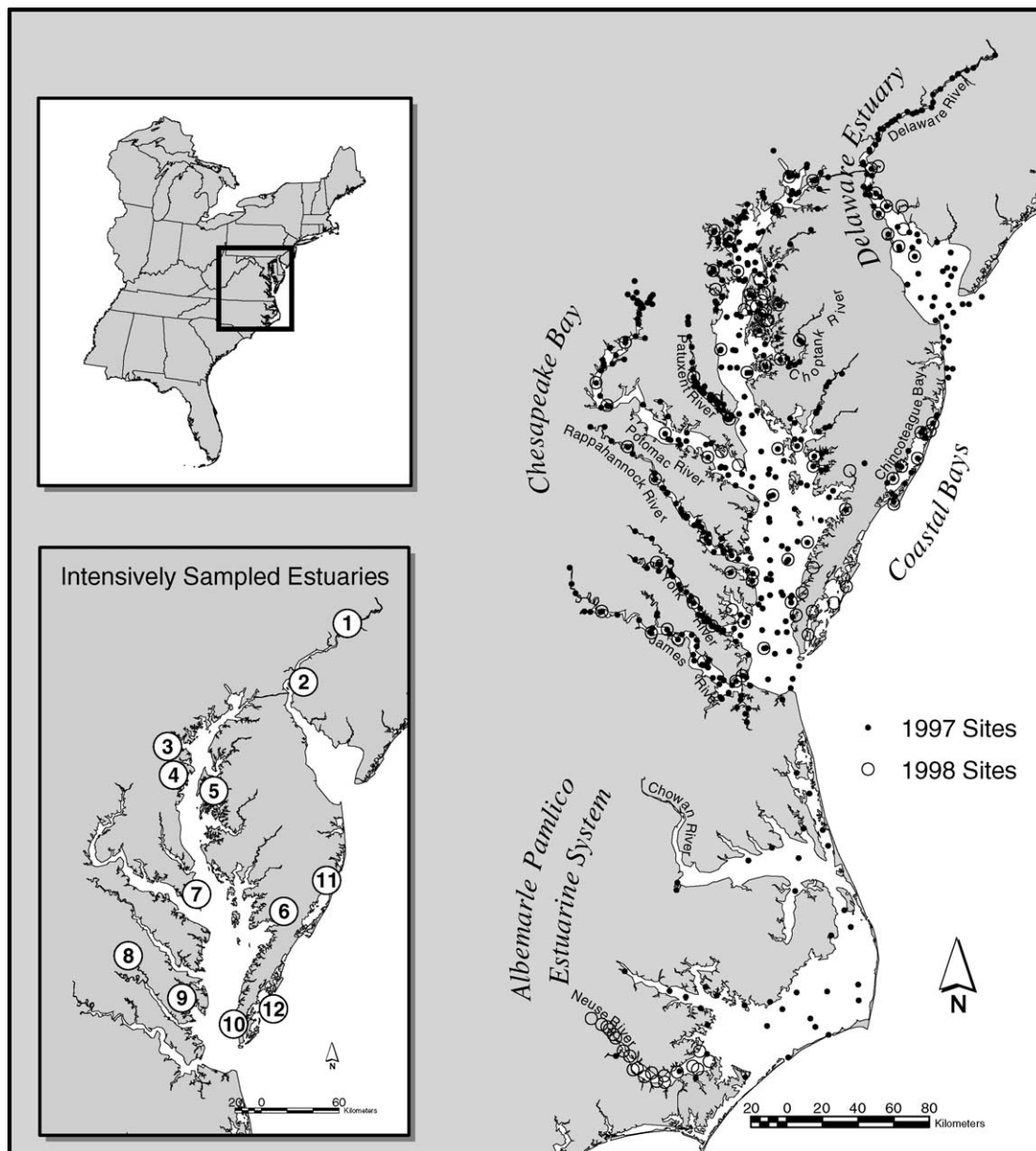


Fig. 1. MAIA-Estuaries monitoring stations. The intensively sampled estuaries are: (1) Schuylkill River, (2) Salem River, (3) Severn River, (4) South River, (5) Eastern Bay, (6) Pocomoke River, (7) St. Jerome Creek, (8) Pamunkey River, (9) Mobjack Bay, (10) Cherrystone Inlet, (11) Sinepuxent Bay, (12) VA Coastal Bays.

in APES. EPA sampled at stations in the 12 intensively sampled estuaries and in smaller estuaries not monitored by other partners. In cases where the host organization did not normally collect some types of samples, sampling protocols were augmented and field crews were trained to sample for the full suite of MAIA-Estuaries water, sediment, and benthic assemblage indicators.

2.2. MAIA-Estuaries indicators

The indicators used in MAIA-Estuaries were selected by the partners in response to the needs of regional environmental managers (USEPA, 1998; Paul et al.,

1999). Included were the core suite of indicators from the EMAP-VP estuarine study (Strobel et al., 1999) plus additional water-quality indicators chosen to address eutrophication issues (Table 1). Samples and in situ measurements were collected for characterizing: (1) physical and chemical habitat (depth, temperature, salinity, dissolved oxygen, pH, water clarity, organic carbon in sediments, and grain size of sediments); (2) water quality (dissolved and particulate nutrients, total suspended solids, chlorophyll *a*, and phaeophytin); (3) contamination in sediments (total metals, simultaneously extracted metals (SEM), acid-volatile sulfide (AVS), polycyclic aromatic hydrocarbons (PAHs),

Table 1
MAIA-Estuarines indicators and methods

Analyte	Min. detection Limit	Units	Method	Reference
<i>Physical habitat parameters</i>				
Temperature	0.1	°C	Hydrolab Datasonde	Strobel (1998)
Salinity	0.1	ppt	"	"
Dissolved oxygen	0.1	mg/l	"	"
pH	0.01	pH unit	"	"
Secchi depth	0.1	Meter	Measured once per station	"
Total organic carbon	0.1	%	OI Analytical Model 700 TOC Analyzer	USEPA (1995)
% Silt/clay (grainsize)	0.1	%	63µ filtration; gravimetric analysis	"
<i>Water-quality parameters</i>				
Silica	0.01	mg Si/l	Technicon Auto-Analyzer II	D'Elia et al. (1997)
Orthophosphate	0.0006	mg P/l	Technicon Auto-Analyzer II	"
Ammonium	0.003	mg N/l	Technicon Auto-Analyzer II	"
Nitrate plus nitrite	0.0002	"	Technicon Auto-Analyzer II	"
Nitrite	0.0002	"	Technicon Auto-Analyzer II	"
Total dissolved nitrogen	0.02	"	Alkaline digestion; Technicon Auto-Analyzer II	"
Total dissolved phosphorus	0.001	mg P/l	"	"
Dissolved organic carbon	1.0	mg C/l	Shimadzu 5050A TOC Analyzer	"
Particulate organic carbon	0.06	"	Exeter CE-440 Elemental Analyzer	"
Particulate organic nitrogen	0.011	mg N/l	"	"
Particulate phosphorus	0.001	mg P/l	Acid digestion; Technicon Auto-Analyzer II	"
Total suspended solids	0.8	mg/l	Gravimetric analysis	"
Chlorophyll <i>a</i>	0.7	µg/l	Turner Design TD700 fluorometer	"
Phaeophytin	0.1	"	"	"
<i>Contaminants in sediments and fish/crab tissue (based on NOAA NS&T methods)^a</i>				
Si, Al (sediments only)	30,000	µg/g ^b	Flame AA	Lauenstein and Cantillo (1993)
Cr, Cu, Fe, Mn, Ni, Zn	0.01	"	ICP	"
Ag, As, Cd, Pb, Sn, Tl	0.001	"	Graphite furnace AA	"
Hg	0.002	"	Cold vapor AA	"
Se	0.006	"	Hydride generation atomic fluorescence	"
PAHs ^c	0.01	ng/g	GC/MS	"
PCBs ^d	0.01	"	GC/ECD	"
Pesticides ^e	0.01	"	GC/ECD	"
Butyltins ^f (sediments only)	0.01	"	GC/FID	"
<i>SEM in sediments</i>				
Cd, Cu, Ni, Pb, Zn	0.001	µmol/g	ICP	USEPA (1991)
AVS	0.01	"	Spectrophotometer	"
<i>Sediment toxicity</i>				
Microtox [®] —whole sediment assay				Microbics (1992)
Microtox [®] —organic-extract assay				Johnson and Long (1988)
<i>Amplescia abdita</i> bioassay				ASTM (1991); USEPA (1995)
<i>Biotic conditions</i>				
Diversity and abundance of benthic macroinvertebrates				
Diversity and abundance of fish and invertebrates				
External pathology and spleen macrophage aggregates in fish				

^a NOAA NS&T: National Oceanic and Atmospheric Administration National Status and Trends Program. AA: atomic absorption; ICP: optical-emission ionically coupled plasma; GC/MS: GC/mass spectrometer; GC/ECD: GC/electron capture detector; GC/FID: gas chromatography/flame ionization detector.

^b Reported based on dry weight of sediments and wet weight of tissue.

^c PAHs: acenaphthene, acenaphthylene, anthracene, benz(a)anthracene, benz(a,e)pyrene, benzo(b,k,b+k)fluoranthene, benzo(g,h,i)perylene, biphenyl, chrysene, dibenz(a,h)anthracene, fluoranthene, fluorene, indeo(1,2,3-c,d)pyrene, naphthalene, 1-methylnaphthalene, 2-methyl naphthalene, 2,6-dimethylnaphthalene, 2,3,5-trimethylnaphthalene, perylene, phenanthrene, 1-methylphenanthrene, pyrene, total PAHs.

^d PCBs: congeners 8, 18, 28, 29, 44, 52, 66, 87, 101, 105, 118, 128, 138, 153, 170, 180, 187, 195, 201, 206, 209, total PCBs.

^e Pesticides: aldrin, chlordane (alpha-, gamma-, oxy-), dieldrin, dibenzothiophene, DDD (2,4'; 4,4'), DDE (2,4'; 4,4'), DDT (2,4'; 4,4'), endosulfan I & II, endrin, heptachlor, heptachlor epoxide, hexachlorobenzene, hexachlorohexane (alpha-, beta-, delta-), lindane, mirex, trans-nonachlor.

^f Butyltins: mono-, di-, tri-, tetra-.

polychlorinated biphenyls (PCBs), pesticides, butyltins, and sediment toxicity); (4) contaminants in fish and crab tissue (total metals, PAHs, PCBs, and pesticides); and (5) biotic condition (diversity and abundance of benthic invertebrates, fish and shellfish; determination of external pathology and spleen macrophage aggregates in fish). Fish and shellfish were surveyed only in 1998.

2.3. Sampling and analytical methods

A Hydrolab Datasonde was used to measure in situ values of physical habitat indicators at 1-m intervals in the water column, and water clarity was determined with a Secchi disk. Water samples were collected with a 5-l Go-Flo[®] bottle in the surface and bottom layers (1 m from the air and sediment interfaces, respectively), and filtered with 0.7- μ m glass-fiber filters. The water and filters were frozen for later analysis. A wide range of nutrients were measured, including the particulate and dissolved inorganic and organic components of nitrogen and phosphorus (Table 1). Replicate field samples were analyzed from 6% of the stations to evaluate the sampling procedure. Analytical methods used on water samples were as described in D'Elia et al. (1997).

Sediment was collected with a 0.04-m² Young-modified Van Veen grab sampler, and physical, chemical, and toxicological characteristics of the sediments were determined from composites of the upper 2 cm from each station. The NOAA (NS&T) suite of chemical contaminants (Table 1) were measured in the composites. Sediments analyzed for total metals were dried and completely digested in nitric/hydrofluoric acids (acid persulfate for mercury). For measuring AVS and SEM, wet sediments were treated with 1-M HCl (USEPA, 1991). For the organic analyses, sediments were extracted with the NS&T procedures (Lauenstein and Cantillo, 1993). All samples were stored frozen before being analyzed.

Three measures of sediment toxicity were generated. (1) Static 10-day survival tests for *Ampelisca abdita* (ASTM, 1991; USEPA, 1995) were run at 20 °C and 30 ppt salinity on sediments from 401 stations. Total ammonia in pore water was first measured, and the sediment flushed if the level exceeded 20 mg/l. Sediments were considered toxic if the survival rate of the amphipods was <80% of a negative control ($\alpha = 0.05$). (2) A solid-phase Microtox[®] bioassay was performed on whole sediments (Microbics, 1992) from 326 stations. A dilution series of sediments in 2% saline (0.01–10% sediment) was inoculated with the photoluminescent bacterium *Vibrio fischerii*, incubated for 20 min, filtered, and analyzed with a Microtox[®] Model 500 Analyzer for the remaining luminescence. A log-linear regression model was used to determine the EC₅₀ (the sediment concentration that reduced the luminescence by 50% relative to a nontoxic control), and corrected for mois-

ture of the sediment. The toxicity criteria depended on grain size because muddy sediments can diminish luminescence (Ringwood et al., 1997). Sediments with silt fractions $\geq 20\%$ were considered to be toxic if the EC₅₀ was $\leq 0.2\%$, and sediments with silt fractions <20% were toxic for EC₅₀ $\leq 0.5\%$. (3) An exploratory organic-extract Microtox[®] bioassay (Johnson and Long, 1988) was performed on sediments from 75 stations. The sediments were dried with anhydrous sodium sulfate, extracted with dichloromethane, and exchanged into a mixture of dimethylsulfoxide, toluene, and isopropyl alcohol. A dilution series was then prepared from the extract and analyzed as above. Sediments were considered to be toxic if the EC₅₀ exceeded the EC₅₀ for a reference sediment.

Sediments were also collected for measuring the identity and abundance of infaunal and epifaunal benthic macroinvertebrates. One to three grab samples were taken from each station with the Van Veen grab sampler. The contents were sieved in the field with a 0.5-mm mesh screen and organisms retained on the screen were fixed in 10% buffered formalin and stained with rose bengal. Organisms were identified to the lowest possible taxon, usually species, except for the following groups, which were routinely identified to the indicated level: anthozoa (class), chironomidae (family), hirudinea (class), nemertinea (phylum), oligochaeta (class), ostracoda (subclass), sipuncula (phylum), turbellaria (class), and copepoda (order). The biomass of all specimens of a taxon in a grab sample was calculated as the dry weight after being dried at 60 °C and combusted in an ash oven at 500 °C for 5 h.

Fish and crabs were collected in standard 10-min trawls, with a 15-m otter trawl towed against the tide at 1–3 knots (0.5–1.5 m/s). The identity, abundance, average fork length, and frequency and location of visible pathologies (lumps, growths, ulcers, or finrot) were determined during shipboard inspections for all fish species collected in standardized fish trawls. Spleens of the target species white perch (*Morone americana*), spot (*Leiostomus xanthurus*), and summer flounder (*Paralichthys dentatus*) were preserved for later histological examination for macrophage aggregates. The concentrations of metals, PAHs, PCBs, and pesticides were measured in filets and whole-body composite samples of summer flounder or blue crab (*Callinectes sapidus*).

2.4. Calculated indicators

Total nitrogen (TN) was calculated as the sum of particulate nitrogen and total dissolved nitrogen, and total phosphorus (TP) as the sum of particulate phosphorus and total dissolved phosphorus. Benthic species enumeration and biomass data were used to calculate mean abundances per grab of infaunal species, epifaunal species, spionid polychaetes, and tubificid oligochaetes,

the mean biomass per grab of all species, the total and mean numbers per grab of infaunal species and epifaunal species, and the Shannon–Wiener index (Shannon and Weaver, 1949) and Gleason's D index (Krebs, 1989). A multimetric benthic community index was calculated as a weighted combination of three indicators (salinity-adjusted Gleason's index, salinity-adjusted abundance of tubificids, and abundance of spionids). This index is the same as that developed by Paul et al. (2001) during the 1990–1993 EMAP effort in the Virginian Province, using discriminant analysis to distinguish degraded sites from nondegraded sites. Degraded sites were considered to be those with dissolved oxygen ≤ 2 mg/l in bottom water, excessive contaminants in sediments, or toxic sediments. Indexes less than or equal to zero designated degraded benthic conditions. Stations in the APES were evaluated by a related benthic index developed for the EMAP-Carolinian Province (CP) estuarine study (Hyland et al., 1998). Because the threshold of impairment for this index was 3, the APES indexes were calculated by subtracting 3 from the CP indexes.

2.5. Data analysis

Associated with each station was a weighting factor (inclusion probability) that equaled the estuarine area represented by the station. Each station was assigned to a stratum identified with an estuary, a tidal tributary, or a class of small estuaries in one of the four estuarine systems (Table 2). The environmental condition was expressed as the percent of estuarine area with conditions above or below a designated threshold of degradation. These estimates were computed for three nested spatial scales: (1) each stratum; (2) each of the four estuarine systems of the mid-Atlantic region; and (3) the overall MAIA region. The percent of degraded area in a stratum was calculated by summing the areas represented by stations satisfying a specified impairment criterion and dividing by the total area contributing data to the stratum. The systemwide impairment was estimated as the average of the stratum estimates just described, weighted by area (stratum area divided by system area). The regionwide impairment was estimated as the weighted average of system estimates of condition. The 95% confidence limits of these estimates were calculated by the procedure of Heimbuch et al. (1995).

3. Results and discussion

3.1. Indicators of estuarine condition

Before planning MAIA-Estuaries, we reviewed estuarine conditions in the mid-Atlantic region and canvassed environmental managers of large and small

estuaries to determine which environmental issues were considered the most pressing (USEPA, 1998; Paul et al., 1999). Key concerns that emerged included water quality, particularly the enrichment of nutrients (Twilley et al., 1985); increased frequency of algal blooms (Harding and Perry, 1997); increased hypoxia and anoxia (Taft et al., 1980); and diminished water clarity and increased loss of submerged aquatic vegetation (Kemp et al., 1983). There were also concerns about contaminated sediments (Costa and Sauer, 1994), toxic sediments (USEPA, 1997), contaminated fish tissue (O'Connor and Beliaeff, 1995), and impairments to benthic communities (Strobel et al., 1995). Based on this review (USEPA, 1998), we augmented the core indicators from EMAP-Estuaries (Hunsaker and Carpenter, 1990) with additional measures of water quality, particularly chlorophyll *a* and a full complement of nutrient species (Table 1).

Here we focus on 10 indicators that address several important issues in the region (Table 3). Six of them characterize the extent of estuarine eutrophication, three evaluate the degree of sediment contamination, and one multimetric benthic index is used to indicate impairment to the benthic community. Each indicator has an associated threshold of degradation (Table 3). Because no single indicator can properly estimate overall estuarine condition, we rely on a preponderance of evidence (multiplicity of indicators) when evaluating degradation.

3.2. Estuarine eutrophication

"Cultural eutrophication" has been defined as an anthropogenically induced increase in the rate of primary production (Nixon, 1995). This definition is an improvement over those based solely on nutrient enrichment or adverse effects of eutrophication such as hypoxia or SAV loss—issues which are influenced by processes other than eutrophication. However, the rate of organic production is difficult to measure directly and is rarely determined in large-scale monitoring programs. Here, we represent various aspects of eutrophication with six indicators (Table 3). Chlorophyll *a* in surface water and total organic carbon (TOC) in sediments reflect the production rate of organic material. TN and TP in surface water are used to evaluate nutrient enrichment—the most likely cause of eutrophication (NRC, 2000). And water clarity (Secchi depth) and dissolved oxygen (DO) in bottom water are used to highlight potential problems often associated with eutrophication (Orth et al., 1997; Diaz and Rosenberg, 1995).

The ranges and distributions of concentrations of these six indicators, relative to thresholds of degradation are presented in Fig. 2. Enriched nutrients were evident in parts of each system, especially in the three Delaware Estuary rivers (on average, 3–4 times higher than elsewhere in the region). Chlorophyll *a* was high in the

Table 2
MAIA-Estuarines systems, strata, and stations

System	Strata	Area (km ²)	Number of stations			Sampled by ^a
			Sampled for all analyses			
Delaware Estuary	Delaware Bay	1784	31			NOAA
	Delaware River	245	30			NOAA
	Small Estuaries ^b	30	2			USEPA
	Total	2059	63			
Maryland and Virginia Coastal Bays	Chincoteague Bay	208	12			NPS
	Small Estuaries ^b	160	5			USEPA
	Total	368	17			
Albemarle–Pamlico Estuarine System (APES)	Albemarle–Pamlico Sounds	6063	21			NOAA, UNC
	Chowan River	129	10			NOAA
	Neuse River	412	20			NOAA
	Small Estuaries ^b	1443	15			USEPA
	Total	8047	66			
			Sampled for specific analyses ^c			
			Water	Sediment	Benthic	
Chesapeake Bay	Mainstem	6527 ^d	43	36	61	CBP
	Patuxent River	138	11	5	25	CBP
	Potomac River	1085 ^d	28	14	25	CBP
	Rappahannock River	340	12	10	25	CBP
	York River	170	8	5	25	CBP
	James River	577	20	14	25	CBP
	Pocomoke/Tangier Sounds	804	6	4	6	CBP
	Eastern Tributaries	654	19	6	35	CBP
	Small Estuaries ^b	2315	18	17	17	USEPA
	Total	12,610	165	111	244	
MAIA region total		23,083				
Intensively sampled estuaries	Schuylkill River	2.4	10			USEPA
	Salem River	1.9	10			USEPA
	Severn River	24.7	29			USEPA
	South River	12.7	27			USEPA
	Eastern Bay	141	10			USEPA
	St. Jerome Creek	4.4	10			USEPA
	Pocomoke River	8.2	5			USEPA
	Pamunkey River	17.8	11			USEPA
	Mobjack Bay	149	10			USEPA
	Cherrystone Inlet	5.4	10			USEPA
	Sinepuxent Bay	14.2	5			USEPA
	Virginia Coastal Bays	144	11			USEPA

^a NOAA: National Oceanic and Atmospheric Agency; USEPA: US Environmental Protection Agency; NSP: National Park Service; UNC: University of North Carolina; CBP: Chesapeake Bay Program.

^b Small estuaries: a randomly selected subset of all small estuaries in designated system with areas < 100 km².

^c Separate sampling networks are maintained by the CBP for sampling water, sediments, and benthic community. Samples are collected for multiple analyses at some stations.

^d These values represent areas sampled for sediment and benthic analyses. Areas for water analyses are 5340 km² for the mainstem and 1151 km² for the Potomac River. Total Chesapeake and MAIA regional areas are adjusted accordingly for the water analyses.

western tributaries of Chesapeake Bay and Salem River, but low in the nutrient-rich Delaware and Schuylkill rivers. The inconsistent correlation between nutrients and algae in the Delaware Estuary may reflect the fact that algal production is probably light-limited due to the high turbidity there (Pennock et al., 1994). Alternately, it may simply mean that the dynamic relationship between nutrients and algal production cannot be cap-

tured properly in “snapshot” monitoring efforts such as MAIA-Estuarines. Secchi depths were commonly less than 0.5 m throughout the region (Fig. 2), indicating limited water clarity that may be attributed with suspended sediment material or algal blooms. Water clarity was particularly poor in the coastal bays. Bottom-layer DO values ≤ 5 mg/l were largely restricted to the mainstem and deeper portions of the western tributaries in

Table 3

MAIA-Estuarines indicators of eutrophication, sediment contamination, and benthic condition

Eutrophication indicators	Notes regarding indicators and thresholds
<i>Chlorophyll a in surface water</i> Threshold: Chl <i>a</i> > 15 µg/l	Chlorophyll <i>a</i> is a measure of phytoplankton biomass. Because of dynamic and patchy nature of algal blooms, this indicator represents a minimum estimate of organic production. The threshold is equal to the restoration goal for the survival and propagation of SAV in Chesapeake Bay (Batiuk et al., 2000). While this threshold value may not be appropriate for SAV restoration in all estuaries, it is useful as a reference level of organic productivity. NOAA's Estuarine Eutrophication Survey used a threshold of 20 µg/l (Bricker et al., 1999). <i>Caveat</i> : chlorophyll <i>a</i> does not measure macroalgae, which may dominate algal productivity in small estuaries such as the coastal bays.
<i>Total organic carbon in sediments</i> Threshold: TOC > 3%	TOC reflects the accumulation of organic material in sediments, and thus is a measure of organic productivity. Factors other than eutrophication also affect TOC content, e.g., redistribution by currents, and consumption by benthic organisms. The threshold is same as that used in EMAP-Virginian Province analysis, based on finding that TOC values greater than 3% were associated with impaired benthic communities as measured by the benthic index, while TOC values less than 1% were not (Paul et al., 1999).
<i>Total nitrogen in surface water</i> Threshold: TN > 1.0 mg N/l	Total nitrogen (TN) represents the sum of all forms of organic and inorganic dissolved and particulate N-nutrients, and is the most likely cause of recent eutrophication in estuaries (NRC, 2000). TN is the measure recommended in the draft report of the Nutrient Criteria Technical Guidance Report: Estuarine and Coastal Waters (USEPA, 2001) for use as future nutrient criteria. No specific criteria have yet been set; therefore, the threshold used here is the 75th percentile of all TN values measured in the MAIA-Estuarines program. NOAA's Estuarine Eutrophication Survey used a total dissolved nitrogen value of 1.0 mg N/l to indicate high N-nutrient levels (Bricker et al., 1999).
<i>Total phosphorus in surface water</i> Threshold: TP > 0.1 mg P/l	Total phosphorus (TP) is the sum of all forms of organic and inorganic, dissolved and particulate P-nutrients, and is a possible cause of eutrophication in estuaries (Sundareshwar et al., 2003). The Nutrient Criteria Technical Guidance Report: Estuarine and Coastal Waters (USEPA, 2001) recommends using TP as the measure of P-nutrient availability, but no criteria of impairment have yet been set. The threshold used here is the 75th percentile of all TP values measured in the MAIA-Estuarines program and is equal to the total dissolved phosphorus limit used in NOAA's Estuarine Eutrophication Survey (Bricker et al., 1999).
<i>Water clarity (Secchi depth)</i> Threshold: Secchi depth ≤ 1 m	Poor water clarity may indicate algal bloom activity, but is also attributed to factors unrelated to eutrophication, such as suspended inorganic particles or tannins. Poor clarity is a threat to the survival of submerged aquatic vegetation (SAV). There are no established criteria for water clarity employing Secchi depth directly. Secchi depth (SD) can be compared to the light extinction coefficient K_d , which describes the exponential decrease of illumination I_z/I_0 with water depth z : $I_z/I_0 = \exp(-K_d * z)$. Batiuk et al. (2000) found an expression which is useful for estuaries: $SD * K_d = 1.45$. Thus, an SD of 1.0 m is equivalent to the transmission of 23% of ambient light at 1 m depth, comparable to the restoration goals recommended for the survival of SAV in Chesapeake Bay (Batiuk et al., 2000). This SD threshold is equal to the limit used in NOAA's Estuarine Eutrophication Survey (Bricker et al., 1999), and is equivalent to the "Bernie Fowler Sneaker Index" measured annually since 1988 by the former Maryland state senator.
<i>Dissolved oxygen in bottom water</i> Threshold: DO ≤ 5 mg/l	Oxygen depletion in bottom water is caused, in part, by the decay of excess organic material. Prolonged exposure of biota to oxygen concentrations less than 5 mg/l may result in altered behavior, reduced growth, adverse reproductive effects, and mortality (Vernberg, 1972; Diaz and Rosenberg, 1995). EPA's proposed saltwater quality criteria cite DO thresholds of 2.3 and 4.8 mg/l (USEPA, 2000). Most states have set their water-quality standard for DO at 5 mg/l. <i>Caveat</i> : Short-term hypoxic conditions may also occur in shallower water during the night, when oxygen demand from respiration exceeds supply. This indicator does not measure this effect.
Sediment contamination indicators	Notes regarding indicators and thresholds
<i>Metal contamination in sediments</i> Threshold: Any ERL exceedance	Long and Morgan (1990) identified nine metals which adversely affects biological organisms in estuaries. The ERL value is the concentration levels below which adverse bioeffects on benthic organisms are unlikely; the ERM value is the concentration above which adverse effects are likely. The metals, and ERL, ERM values (mg/g dry wt.) are: As: 8.2, 70; Cd: 1.2, 9.6; Cr: 81, 370; Cu: 34, 270; Pb: 47, 220; Hg: 0.15, 0.71; Ni: 21, 52; Ag: 1.0, 3.7; Zn: 150, 410 (Long et al., 1995). <i>Caveats</i> : This method does not evaluate the interaction of complex mixtures of chemicals (Wenning and Ingersoll, 2002), nor does it account for the possible mitigating effects of organic compounds that may bind toxicants and render them harmless (USEPA, 1993).
<i>Organics contamination in sediments</i> Threshold: Any ERL exceedance	The Long and Morgan approach is also used to characterize levels of organic toxicants in sediments. The organic compounds, ERL, and ERM values (ng/g dry wt.) are: acenaphthene: 16, 500; acenaphthylene: 44, 640; anthracene: 85, 1100; fluorene: 19, 540; 2-methyl naphthalene: 70, 670; naphthalene: 160, 2100; phenanthrene: 240, 1500; benz(a)anthracene: 261, 1600; benzo(a)pyrene: 430, 1600; chrysene: 384, 2800; dibenzo(a,h)anthracene: 63, 260; fluoranthene: 600, 5100; pyrene: 670, 2600; 4,4'-DDE: 2.2, 27; low MW PAH (sum of 2- and 3-ring PAHs): 550, 3160; high MW PAH (sum of 4- and 5-ring PAHs): 1700, 9600; total PAH (sum of all measured PAHs): 4000, 45000; total DDT (sum of 2,4' and 4,4' congeners of DDD, DDE and DDT): 1.6, 46; total PCBs: 23, 180 (Long et al., 1995). See caveats above.

(continued on next page)

Table 3 (continued)

Sediment contamination indicators	Notes regarding indicators and thresholds
<i>Sediment toxicity (amphipod survival)</i> Threshold: Survival $\leq 80\%$	Sediment toxicity is evaluated by measuring the survival rate of the marine amphipod <i>Ampelisca abdita</i> (ASTM, 1991; USEPA, 1995). The National Status and Trends and Environmental Mapping and Assessment programs have conducted surveys of sediment toxicity throughout the US since 1981, consistently using thresholds of 80% and 60% to designate toxic and severely toxic conditions (ASTM, 1991).
Benthic community condition	Notes regarding indicator and threshold
<i>Benthic community index</i> Threshold: Benthic index ≤ 0	This benthic index was developed with data compiled during the 1990–1993 EMAP effort in the Virginian Province (VP) using discriminant analysis to determine a weighted combination of parameters which distinguish impacted and unimpacted sites in the VP (Paul et al., 1999). Index values ≤ 0 designate impacted conditions by definition. Stations in the APES are evaluated by a similar index derived for the EMAP-Carolinian Province (CP) estuarine study (Hyland et al., 1998). The threshold of impairment for the CP index is ≤ 3 ; therefore, the index scores are adjusted by subtracting 3 from the APES values and are evaluated using an impairment threshold of zero.

Chesapeake Bay (Fig. 2). More quantitatively (as indicated by Pearson correlation factors >0.5 , $p \leq 0.05$), chlorophyll *a* was positively correlated with TN and TP in half of the subsystems in Chesapeake Bay and the coastal bays, but poorly correlated in Delaware Bay and APES. Chlorophyll *a* and Secchi depth were inversely correlated in most estuaries other than the Delaware Estuary, suggesting that algal blooms contributed significantly to the poor water clarity during summer. Chlorophyll *a* and TOC were generally unrelated. Bottom-layer DO was not consistently correlated with TN or chlorophyll *a*.

Up to one-fifth of the MAIA region had high nutrients, carbon-enriched sediments, or depleted DO (Table 4 and Fig. 3). One-third had high chlorophyll *a*, and one-half had water-column visibility of 1 m or less. This assessment agrees with the NOAA Estuarine Eutrophication Survey, which queried experts from more than 120 estuaries in the continental US and found that one-third of mid-Atlantic estuaries had moderate to high chlorophyll *a* (>15 – 20 $\mu\text{g/l}$) and 10–20% had potentially harmful levels of nutrients and DO (Bricker et al., 1999).

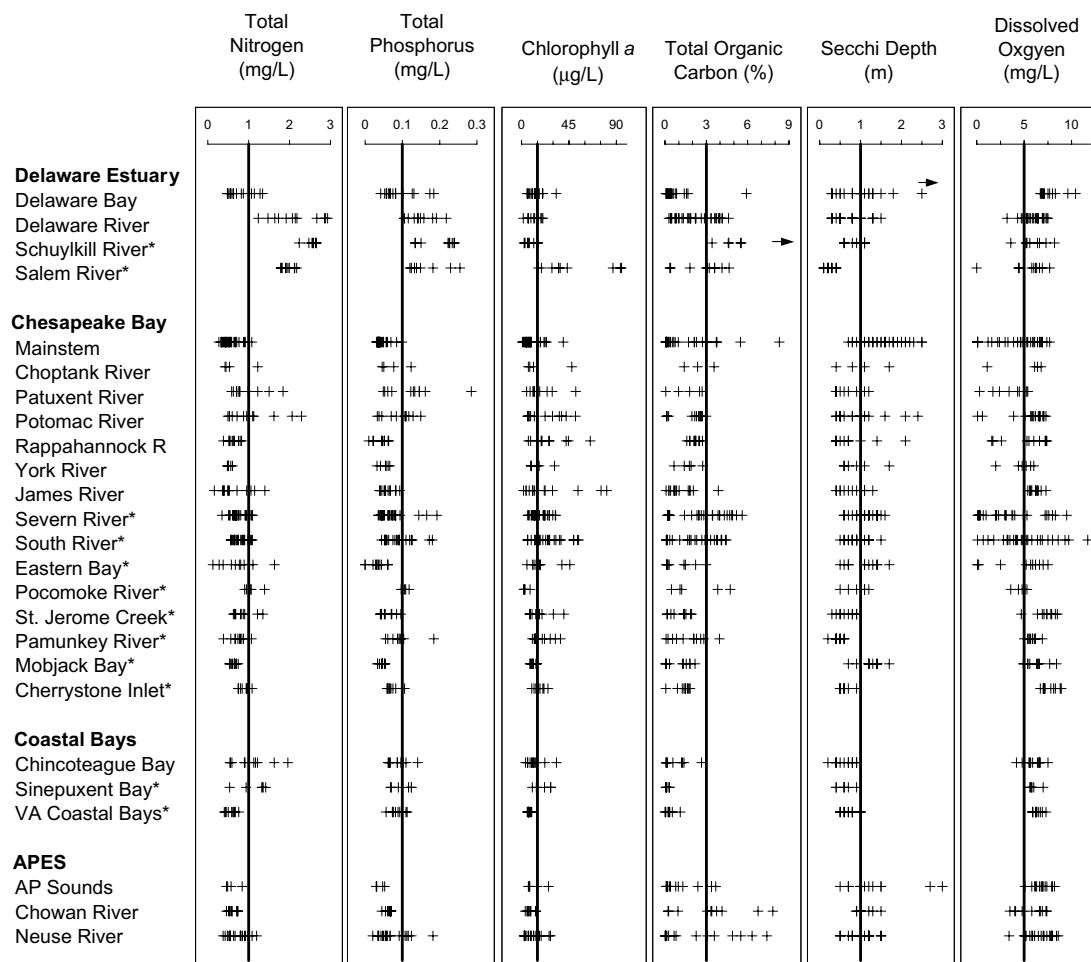
MAIA-Estuaries characterized nutrients with TN and TP rather than the conventional dissolved inorganic nitrogen and phosphorus (DIN and DIP). Since we measured the full complement of dissolved, particulate, organic, and inorganic nutrients, we could examine the relationships between them (Fig. 4). Total nitrogen is the sum of DIN, dissolved organic nitrogen (DON), and particulate organic nitrogen (PON). As expected for late summer, DIN was relatively scarce. The guideline for acceptable DIN levels based on SAV restoration goals in Chesapeake Bay is 0.15 mg N/l (Batiuk et al., 2000). All estuarine systems met this guideline on average, although DIN was far higher in individual northern Chesapeake Bay tributaries and parts of the Delaware Estuary (e.g., >1.7 mg N/l in the Schuylkill and Delaware rivers). DON was appreciable in all systems and similar in concentration to particulate nitrogen. The SAV restoration goals for DIP are 0.02 mg P/l in Chesapeake Bay (0.01 mg P/l in mesohaline waters).

Actual DIP values exceeded the guidelines in all systems except Chesapeake Bay, where phosphate detergents have been banned since 1970.

We can use the SAV restoration guidelines for DIN and DIP to estimate the thresholds for TN and TP. Averaged over the mid-Atlantic region, $\text{TN/DIN} = 5.6$ and $\text{TP/DIP} = 4.6$, suggesting that thresholds for TN and TP are about five times greater than the limits for the dissolved species—about 1 mg N/l and 0.05–0.1 mg P/l, respectively, which are close to the thresholds used here. Although gross extrapolations like this cannot substitute for systematically determining the limits for TN and TP, this calculation supports the threshold values used here. NOAA's Estuarine Eutrophication Survey also used limits of 1 mg N/l and 0.1 mg P/l for total dissolved nitrogen and total dissolved phosphorus, respectively, to indicate high nutrients (Bricker et al., 1999).

3.3. Sediment contamination and toxicity

Estuarine ecosystems are threatened by substances such as toxic trace metals, PAHs, PCBs, and pesticides. These contaminants come to the estuaries from municipal water-treatment plants, urban and agricultural runoff, and atmospheric deposition, and then adsorb onto fine-grained particles and accumulate in depositional basins (Hinga, 1988; Nixon et al., 1986). To the extent that they remain bioavailable, these toxicants pose a risk to benthic communities in contact with the sediments and to organisms throughout the food web. Long et al. (1995) identified 9 toxic metals and 19 toxic organic compounds that induce adverse biological effects in estuarine organisms (Table 3). Effects range-low (ERL) are threshold concentrations below which adverse effects are rarely expected, and effects range-median (ERM) limits are thresholds above which bioeffects are likely to occur. The ERL/ERM approach does not account for interactions of chemicals (Wenning and Ingersoll, 2002) or mitigating effects of organics or sulfides that bind toxicants and render them harmless



* Intensively-sampled estuaries
 APES: Albemarle Pamlico Estuarine System

Fig. 2. Range and distribution of measured values for selected MAIA-Estuarine indicators. Vertical lines mark the thresholds used to denote degradation. ERL and ERM are the “effects range-low” and “effects range-median” values (Long et al., 1995). Concentrations of metals and organics are reported in µg/g (ppm) and ng/g (ppb) dry weight, respectively. Arrows indicate offscale values.

(DiToro et al., 1991). Other approaches have been used to characterize sediment contamination. For instance, chemical concentrations may be normalized to the fraction of silt-clay in sediments (Daskalakis and O’Conner, 1994), TOC contents in sediments (USEPA, 1993), AVSs (DiToro et al., 1991), or crustal metals (Strobel et al., 1995). And the influence of equilibrium partitioning on toxicant availability have been considered (DiToro et al., 1989). We conservatively considered any ERL exceedance as an indication of sediment degradation. The effect of using increasingly stringent criteria of impairment for ERL and ERM exceedances is evident in Fig. 5. Generally, the list of estuaries with contaminated sediments was similar regardless of the criteria used. For instance, estuaries with more than 40% of their area exceeding an ERL were also likely to exceed three or more ERLs or any ERM, and vice versa.

For the MAIA region as a whole, $30\% \pm 7\%$ of the estuarine area exceeded at least one metallic or organic ERL, while $<6\%$ of the area exceeded any ERM (Fig. 5). Sediments in the Delaware, Schuylkill, and Salem rivers of the upper Delaware Estuary contained the greatest concentrations of metals and organic contaminants of the mid-Atlantic region, and the Severn and South rivers also consistently exceeded the ERLs. Arsenic and nickel most often exceeded ERLs in the region, followed in frequency by mercury and zinc. Because the concentrations of organic contaminants were highly correlated; they tended to exceed their ERLs together (Fig. 2). ERL exceedances for organic toxicants were most evident in the Delaware, Schuylkill, Severn, and South rivers.

We evaluated sediment toxicity by using the ASTM (1991) method of measuring the survival of the marine amphipod *Ampelisca abdita* exposed to sediments (Table 3). Only 1% of the sediments in the MAIA region were

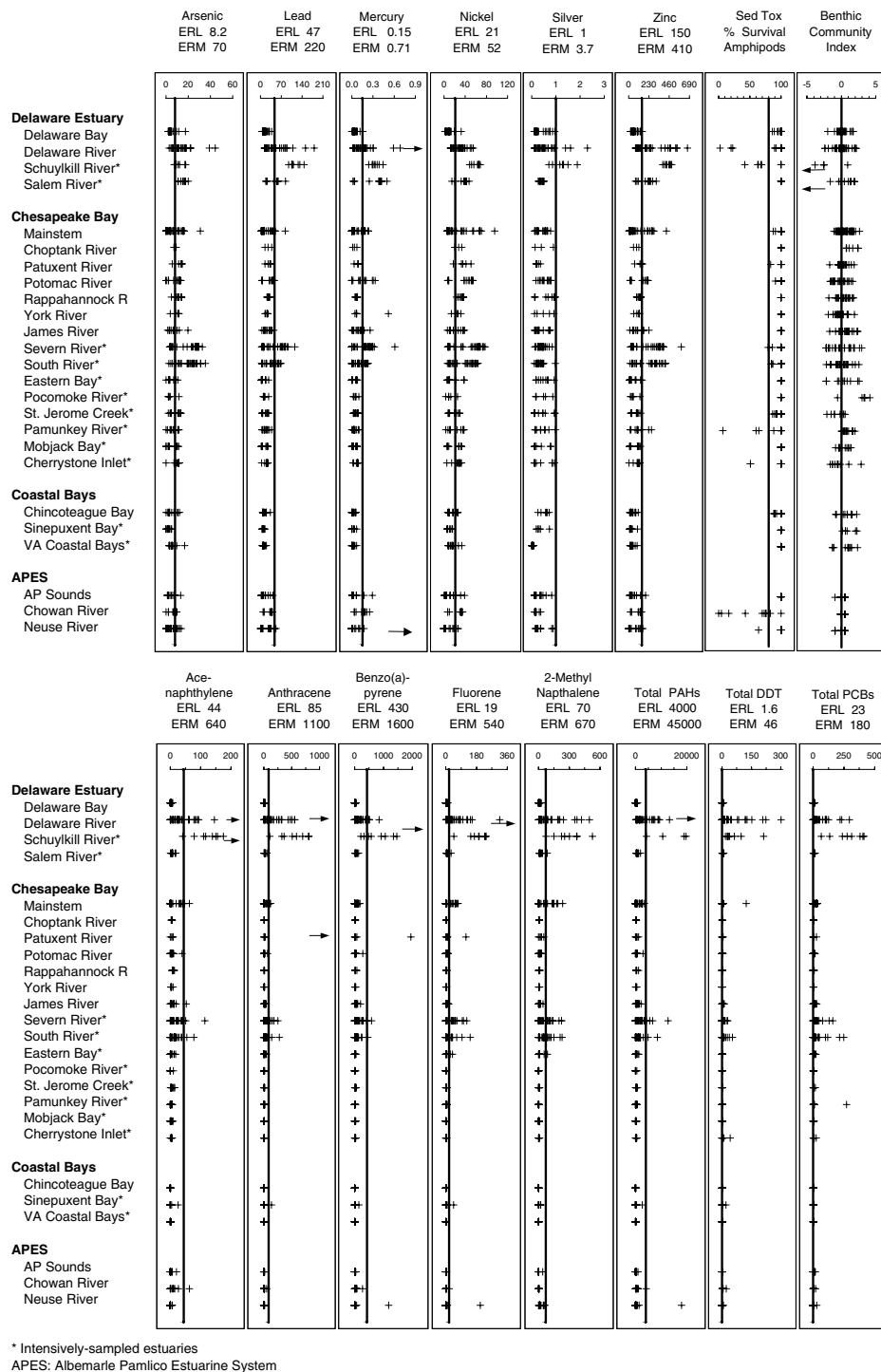


Fig. 2 (continued)

found to be toxic to amphipods, although higher percentages of toxicity were noted for the Delaware, Schuylkill, Pamunkey, and Chowan rivers (Table 4 and Fig. 2). No relationships were noted between amphipod survival rate and potential interferences such as sediment grain size or ammonia concentration in pore water (Spies, 1989). In a NOAA study of 23 US coastal waters, 7% of sediment area was toxic to amphipods; values for

EMAP areas were 10% for the Virginian Province; 2% for the Carolinian Province; 8% for the Louisianian Province; and 0% for the Californian Province (Hameedi et al., 1999).

A visual inspection of amphipod survival rates and toxicant concentrations in Fig. 2 reveal an ambiguous relationship between sediment toxicity and ERL exceedances. For instance, while a toxic response

Table 4
Percent estuarine area exceeding thresholds of degradation

Estuary	Eutrophication											Sediment/benthic								
	TN		TP		Chl <i>a</i>		TOC		Secchi		DO		Metal		Organics		Sed Tox		BI	
<i>MAIA</i>	21	(12)	15	(11)	32	(10)	16	(6)	50	(8)	21	(4)	31	(7)	28	(6)	1	(0)	37	(8)
<i>Delaware Estuary</i>	23	(10)	31	(17)	29	(21)	7	(5)	49	(29)	1	(1)	13	(5)	14	(6)	2	(2)	36	(29)
Delaware Bay	11	(9)	20	(19)	24	(22)	3	(5)	45	(24)	0	(0)	6	(5)	6	(6)	0	(0)	36	(33)
Delaware River	100	(47)	100	(47)	63	(21)	28	(19)	89	(25)	11	(10)	52	(22)	67	(25)	15	(18)	38	(21)
Schuylkill River ^a	100	0	100	(0)	20	(26)	100	(0)	60	(32)	11	(22)	0	(24)	0	(24)	71	(40)	83	(33)
Salem River ^a	100	(0)	100	(0)	100	(0)	60	(32)	100	(0)	30	(26)	30	(0)	80	(20)	0	(0)	40	(32)
<i>Chesapeake Bay</i>	17	(5)	11	(3)	29	(8)	12	(6)	46	(7)	38	(7)	41	(10)	36	(8)	0	(0)	35	(7)
Mainstem	5	(8)	0	(2)	16	(12)	15	(8)	17	(13)	55	(18)	27	(14)	29	(11)	0	(0)	30	(10)
Choptank River	25	(15)	25	(4)	25	(15)	33	(15)	50	(18)	25	(14)	60	(17)	20	(14)	0	(1)	0	(17)
Patuxent River	27	(28)	64	(28)	36	(26)	0	(0)	82	(23)	70	(29)	80	(35)	0	(0)	0	(0)	44	(18)
Potomac River	45	(31)	64	(30)	55	(31)	0	(0)	100	(0)	26	(24)	43	(27)	43	(27)	0	(0)	56	(20)
Rappahannock River	0	(0)	0	(0)	67	(28)	0	(0)	75	(25)	34	(21)	100	(0)	20	(25)	0	(0)	32	(18)
York River	0	(0)	0	(0)	50	(31)	0	(0)	75	(31)	38	(21)	100	(0)	0	(0)	0	(0)	52	(18)
James River	15	(16)	0	(0)	50	(20)	7	(14)	68	(21)	5	(10)	64	(25)	64	(25)	0	(0)	32	(18)
Severn River ^a	18	(14)	11	(12)	41	(18)	45	(18)	45	(18)	71	(18)	7	(16)	14	(18)	4	(7)	62	(18)
South River ^a	12	(14)	23	(16)	73	(19)	35	(19)	89	(12)	54	(19)	22	(19)	30	(19)	0	(0)	59	(19)
Eastern Bay ^a	30	(30)	0	(0)	70	(23)	0	(0)	40	(32)	30	(26)	22	(33)	11	(29)	0	(0)	33	(33)
Pocomoke River ^a	50	(57)	75	(49)	0	(0)	40	(48)	40	(48)	50	(57)	20	(39)	20	(39)	0	(0)	20	(39)
St. Jerome Creek ^a	20	(26)	0	(0)	50	(30)	0	(0)	100	(0)	10	(20)	40	(32)	0	(0)	0	(0)	60	(32)
Pamunkey River ^a	11	(22)	25	(32)	36	(28)	9	(18)	100	(0)	9	(18)	18	(31)	18	(24)	27	(24)	0	(0)
Mobjack Bay ^a	0	(0)	0	(0)	0	(0)	0	(0)	20	(26)	20	(26)	40	(33)	10	(20)	0	(0)	40	(32)
Cherrystone Inlet ^a	11	(22)	11	(22)	50	(33)	0	(0)	100	(0)	0	(0)	80	(26)	60	(30)	10	(20)	80	(26)
<i>Coastal Bays</i>	34	(21)	36	(30)	14	(9)	0	(0)	100	(0)	9	(12)	21	(16)	11	(20)	0	(0)	25	(30)
Chincoteague Bay	50	(32)	30	(29)	0	(0)	0	(0)	100	(0)	17	(21)	36	(29)	0	(0)	0	(0)	9	(23)
Sinepuxent Bay ^a	60	(48)	40	(48)	60	(48)	0	(0)	100	(0)	0	(0)	0	(0)	0	(0)	0	(0)	0	(0)
VA Coastal Bays ^a	0	(0)	20	(26)	0	(0)	0	(0)	100	(0)	0	(0)	18	(24)	9	(18)	0	(0)	30	(30)
<i>Albemarle–Pamlico</i>	25	(31)	16	(30)	37	(25)	24	(14)	54	(18)	3	(4)	20	(13)	20	(13)	2	(0)	41	(17)
Chowan River	0	(0)	0	(0)	0	(0)	70	(29)	70	(29)	40	(31)	70	(29)	60	(31)	80	(31)	40	(31)
Neuse River	9	(15)	1	(1)	41	(28)	33	(26)	51	(29)	9	(15)	33	(26)	8	(15)	0	(0)	50	(29)
Degradation thresholds:	>1 mg/l		>0.1 mg/l		>15 µg/l		>3%		≤ 1 m		≤ 5 mg/l		Any ERL exceedance		Any ERL exceedance		≤ 80%		≤ 0	

The values in parentheses are the 95% confidence limits.

TN: total nitrogen; TP: total phosphorus; Chl *a*: chlorophyll *a*; TOC: total organic carbon in sediments; DO: dissolved oxygen; Sed Tox: sediment toxicity; BI: benthic index.

^aIntensively sampled estuaries.

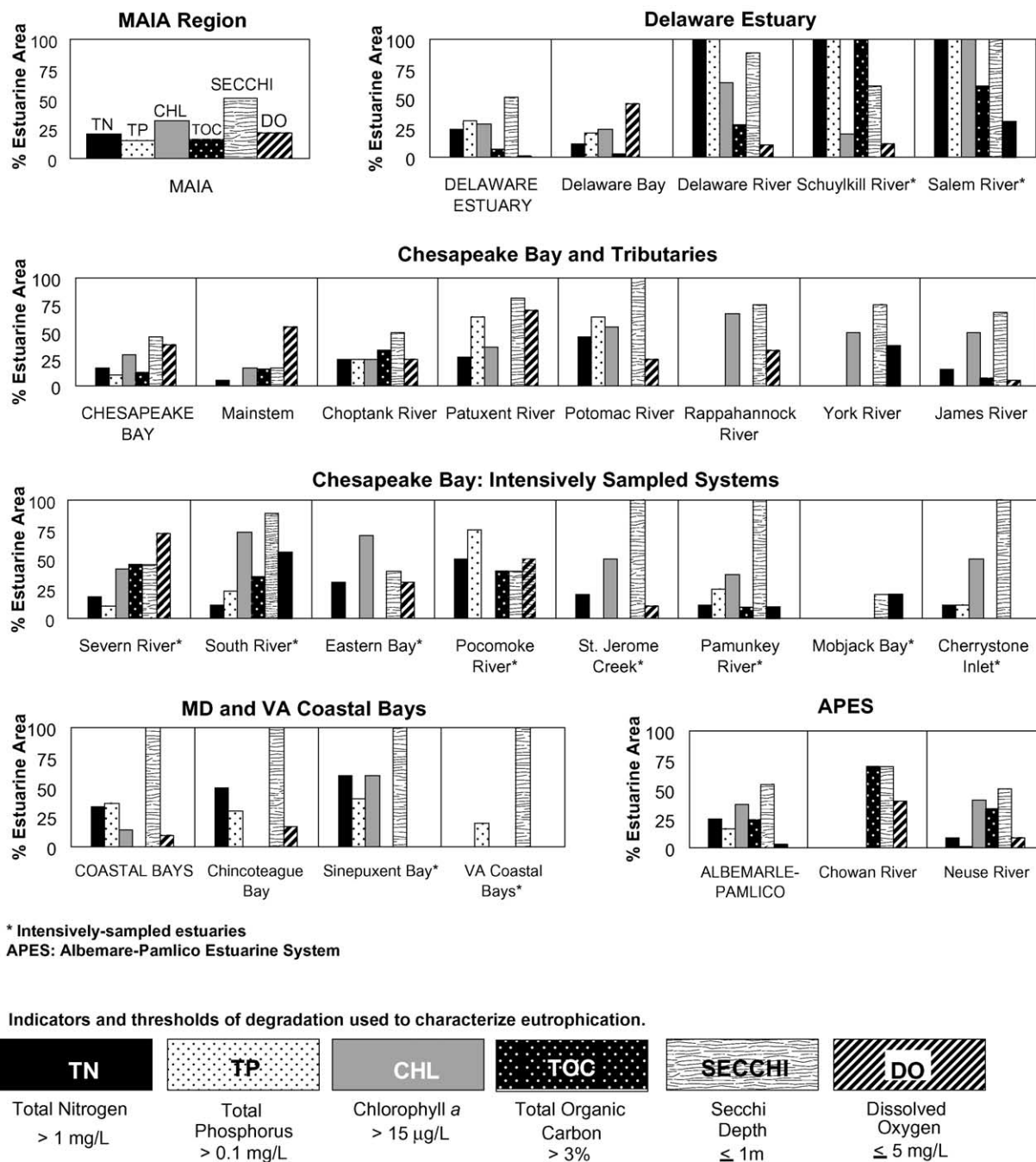


Fig. 3. Nutrients in MAIA-Estuaries 1997–1998. Average total nitrogen and total phosphorus concentrations, weighted by estuarine area.

(amphipod survival <80%) was evident in the highly contaminated Delaware and Schuylkill Rivers, a similar response was absent in the Severn and South Rivers, which also had abundant ERL exceedances. In part, this may reflect the severity of using a strict criteria of mortality to characterize toxicity in the amphipod assay (Hameedi et al., 1999). But it also highlights the need of a more complete analysis of availability of the toxicant constituents, e.g., considering equilibrium partitioning and the mitigating effects of sequestering toxicants with

sulfides or organic compounds (DiToro et al., 1989; DiToro et al., 1991; Daskalakis and O'Conner, 1994; USEPA, 1993).

3.4. Impairment of benthic communities

In ecological monitoring, the earlier focus on chemical measures of condition has recently been broadened to include biological and ecological measures (Karr and

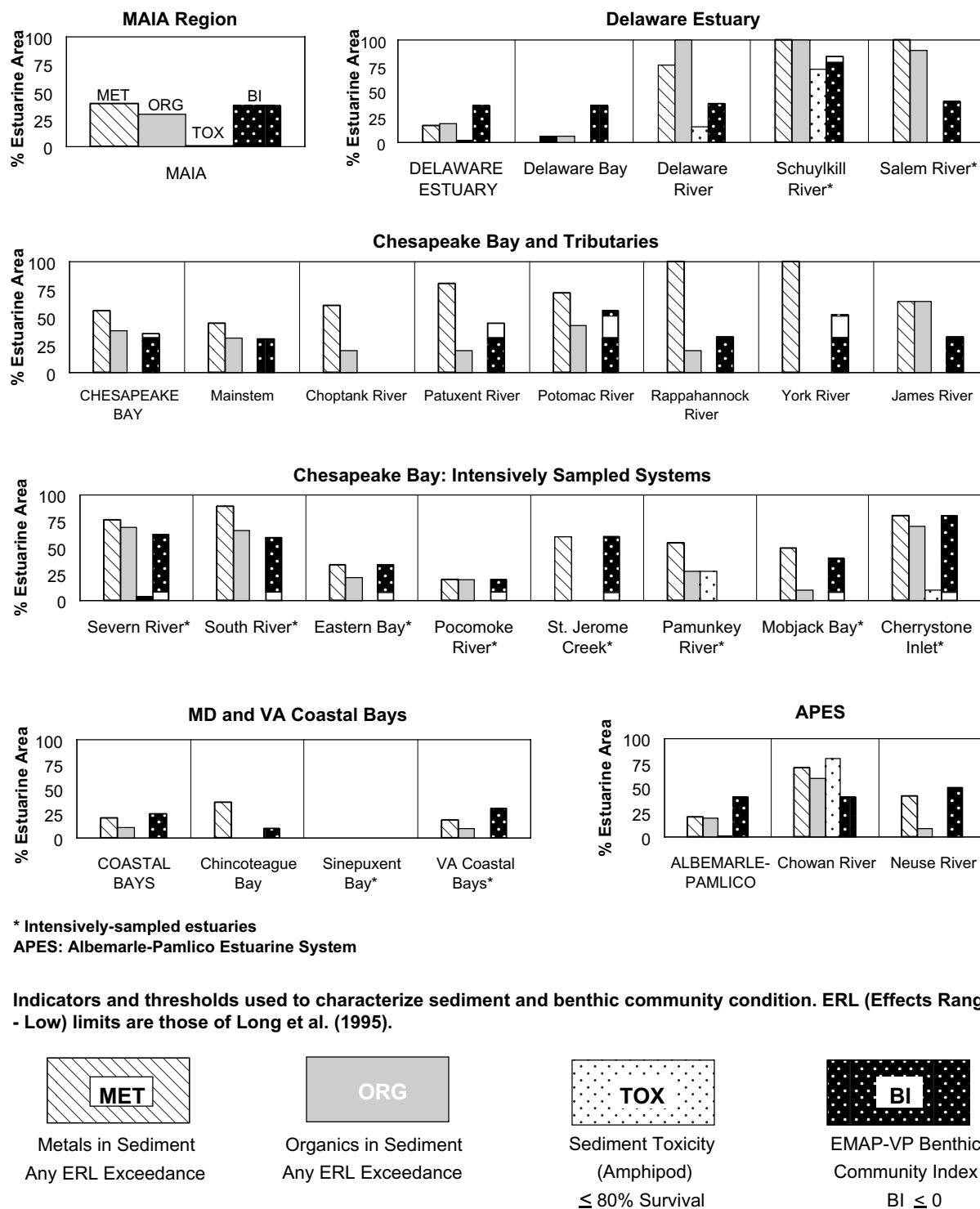


Fig. 3 (continued)

Chu, 1999). In the MAIA study, we examined the biota for indications of ecological condition in estuaries. We focused on macrobenthic communities because they are key components of estuarine ecosystems, whose assemblages have been used to indicate stress and sensitivity to pollution (Pearson and Rosenberg, 1978; Gesteira and

Dauvin, 2000). The benthos is an ideal ecological indicator because it integrates the effects of adverse conditions over months and years—infauna and epifauna live in intimate contact with sediments and are hindered by their relative immobility from avoiding potential pollution or disturbance. Indices expressing characteristics of

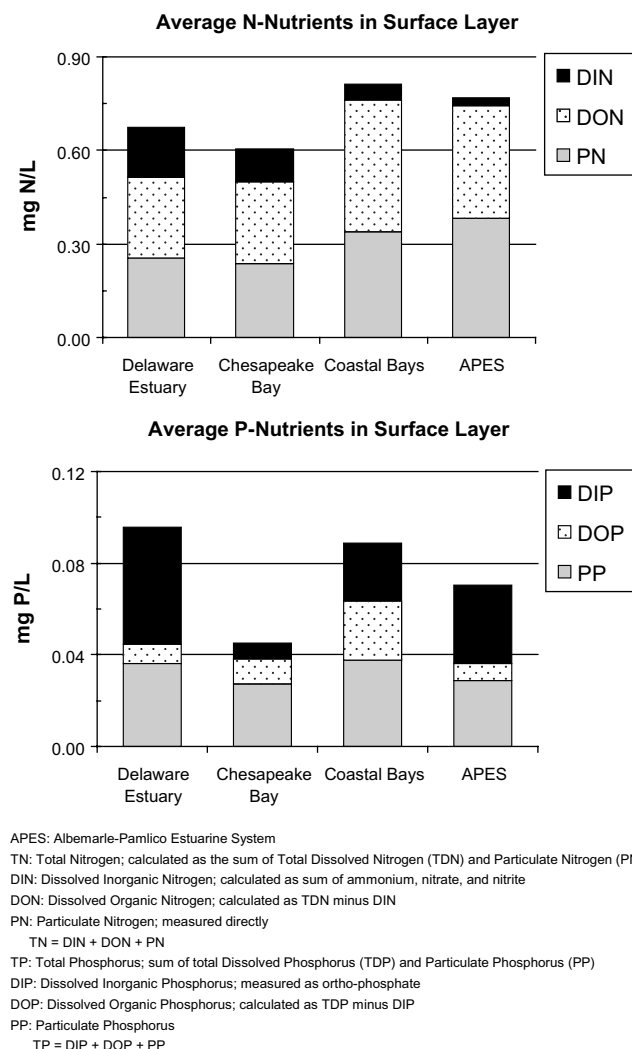


Fig. 4. Percent of mid-Atlantic estuarine area exhibiting degraded conditions for selected MAIA-Estuarines indicators.

macrobenthic communities have been used for decades (Sanders, 1960; Pearson and Rosenberg, 1978; Engel et al., 1994; Weisberg et al., 1997).

Here we characterize the condition of benthic communities with a multimetric benthic index developed in the EMAP-VP estuarine study to distinguish relatively pristine sites from those exhibiting toxic contamination and/or hypoxia (Paul et al., 2001). The index includes terms reflecting the diversity of infaunal and epifaunal species (a positive contribution) and abundances of species associated with degraded conditions (negative contribution). Negative values of the index mean that benthic conditions are impaired. About $37\% \pm 8\%$ of the MAIA region had index values ≤ 0 (Fig. 2). The lowest values were reported for the Schuylkill and Salem rivers. The coastal bays fared better. When the index was compared with other measures of water and sediment quality (Pearson correlation factors >0.5 , $p \leq 0.05$), the benthic index responded to pollution gradients in the

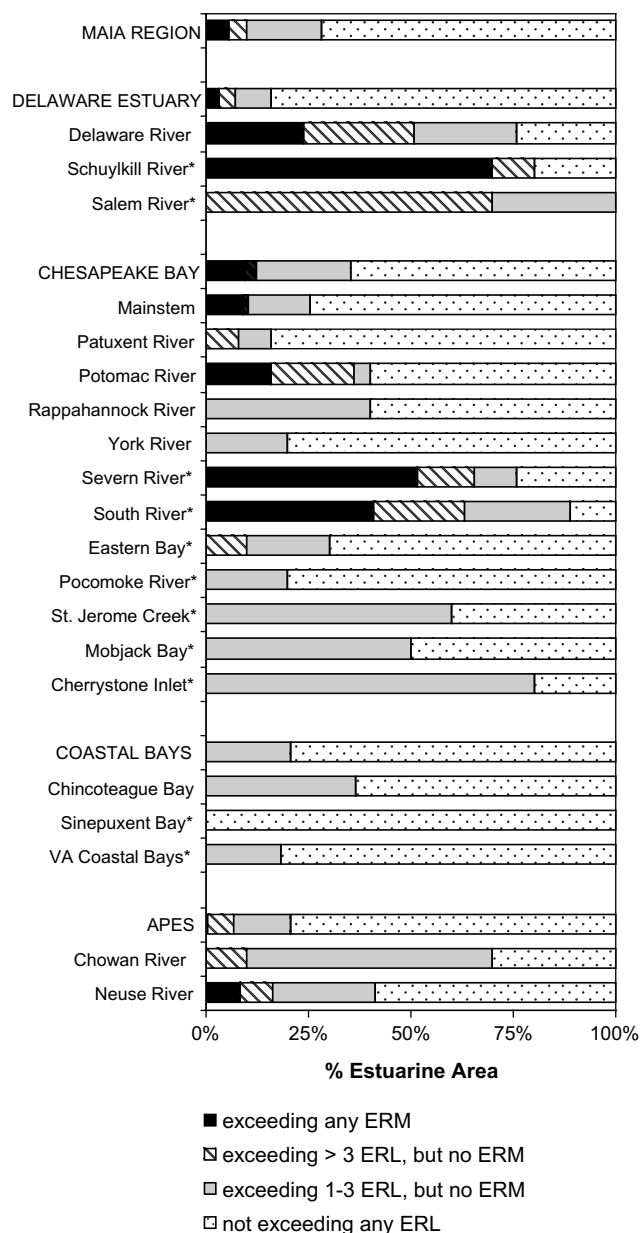


Fig. 5. Percent of estuarine area with contaminated sediments. Different definitions of degradation are denoted by shading.

expected manner. For example, the benthic index was positively correlated with bottom-layer DO, and inversely correlated with sediment contamination (expressed as the number of ERL exceedances).

3.5. Environmental Report Card and Index of Environmental Integrity

The most challenging aspect of large-scale environmental assessments is communicating the meaning and

	Eutrophication						Sediment Contamination			Benthic Condition
	Total Nitrogen	Total Phosph	Tot Org Carbon	Chl a	Water Clarity	Diss Oxygen	Metals	Organics	Sediment Toxicity	Benthic Index
MAIA	21	15	16	31	50	21	31	28	1	37
DELAWARE ESTUARY	23	31	7	29	51	1	13	14	2	36
Delaware Bay	11	20	3	24	45	0	6	6	0	36
Delaware River	100	100	28	63	89	11	52	67	15	38
Schuylkill River*	100	100	100	20	60	11	0	0	71	83
Salem River*	100	100	60	100	100	30	30	80	0	40
CHESAPEAKE BAY	17	11	12	29	46	38	41	36	0	35
Mainstem	5	0	15	16	17	55	27	29	0	30
Choptank River	25	25	33	25	50	25	60	20	0	0
Patuxent River	27	64	0	36	82	70	80	0	0	44
Potomac River	45	64	0	55	100	25	43	43	0	56
Rappahannock River	0	0	0	67	75	33	100	20	0	32
York River	0	0	0	50	75	38	100	0	0	52
James River	15	0	7	50	68	5	64	64	0	32
Severn River*	18	11	45	41	45	71	7	14	4	62
South River*	12	23	35	73	89	56	22	30	0	59
Eastern Bay*	30	0	0	70	40	30	22	11	0	33
Pocomoke River*	50	75	40	0	40	50	20	20	0	20
St. Jerome Creek*	20	0	0	50	100	10	40	0	0	60
Pamunkey River*	11	25	9	36	100	9	16	18	27	0
Mobjack Bay*	0	0	0	0	20	20	40	10	0	40
Cherrystone Inlet*	11	11	0	50	100	0	80	60	10	80
COASTAL BAYS	34	36	0	14	100	9	21	11	0	25
Chincoteague Bay	50	30	0	0	100	17	36	0	0	9
Sinepuxent Bay*	60	40	0	60	100	0	0	0	0	0
VA Coastal Bays*	0	20	0	0	100	0	18	9	0	30
APES	25	16	24	37	54	3	20	20	1	41
Chowan River	0	0	70	0	70	40	70	60	80	40
Neuse River	9	1	33	41	51	9	33	8	0	50
Degraded when: TN TP TOC CHLa SECCHI DO MET ORG TOX BI > 1 mg/L > 0.1 mg/L > 3% > 15 µg/L ≤ 1 m ≤ 5 mg/L Exceeds any ERL ≤ 80% survival ≤ 0										

* Intensively-sampled estuaries

APES: Albemarle-Pamlico Estuarine System

Extent of degradation

	Low: less than 20% of estuarine area has degraded condition
	Moderate: 20% to 40% of estuarine area has degraded condition
	Excessive: more than 40% of estuarine area has degraded condition

Fig. 6. MAIA-Estuaries Environmental Report Card. Numbers in cells are percentages of estuarine area showing degraded condition, based on the thresholds listed at the bottom of the chart.

relevance of raw data to a wide audience. MAIA-Estuaries generated a large quantity of data on a variety of spatial scales. Because this information is valuable to concerned citizens as well as to environmental managers

and scientists, we present it as a Report Card (Fig. 6) that highlights conditions regionally and in individual estuaries, and expresses the results in a relatively easily understood format, while retaining certain quantitative

information for the specialist. The estuaries were grouped by the extent of their area that was degraded: <20%, 20–40%, and >40%, with the break points of 20% and 40% being arbitrary. Even though no particular percentage ranges would likely be appropriate for all ecological indicators, these divisions represent reasonable expectations for low, moderate, and high degradation. The report card also revealed patterns and highlighted the best and worst conditions in the region. For example, water clarity was notably poor in most mid-Atlantic estuaries (Secchi depth ≤ 1 m), depleted

DO in bottom water was largely restricted to the mainstem and tributaries of Chesapeake Bay, much of the Delaware Estuary appeared to be eutrophied, and sediments of the coastal bays were relatively uncontaminated. Similar report cards have been used to summarize conditions in mid-Atlantic estuaries (USEPA, 1998) and in wadeable streams (Boward et al., 1999).

The complex data from MAIA-Estuaries were further distilled by constructing an Index of Environmental Integrity, or IEI (Paul, 2003). The IEI (Fig. 7) is simi-

	Eutrophication	Sediment Contamination	Benthos Condition	Overall IEI
MAIA	4	2	3	3.0
DELAWARE ESTUARY	3	0	3	1.7
Delaware Bay	3	0	3	1.7
Delaware River	4	4	3	3.9
Schuylkill River*	32		6	3.0
Salem River*	5	3	3	3.9
CHESAPEAKE BAY	4	3	3	3.4
Mainstem	2	2	3	2.1
Choptank River	4	3	0	3.0
Patuxent River	5	2	6	3.9
Potomac River	5	4	6	4.7
Rappahannock River	5	3	3	3.9
York River	5	2	6	3.9
James River	4	4	3	3.9
Severn River*	6	0	6	3.4
South River*	6	2	6	4.3
Eastern Bay*	4	1	3	2.6
Pocomoke River*	3	2	3	2.6
St. Jerome Creek*	4	1	6	3.0
Pamunkey River*	3	1	0	1.7
Mobjack Bay*	2	1	3	1.7
Cherrystone Inlet*	4	4	6	4.3
COASTAL BAYS	2	1	3	1.7
Chincoteague Bay	2	1	0	1.3
Sinepuxent Bay*	4	0	0	1.7
VA Coastal Bays*	2	0	3	1.3
APES	33		6	3.4
Chowan River	3	6	3	4.3
Neuse River	4	2	6	3.4

* Intensively-sampled estuaries

APES: Albemarle-Pamlico Estuarine System

Method of calculation: Scores are assigned in each estuary for each indicator

Score = 0 if less than 20% of estuarine area exhibits impairment

Score = 3 if 20% to 40% of estuarine area exhibits impairment

Score = 6 if more than 40% of estuarine area exhibits impairment

Index for eutrophication is average of scores for chlorophyll *a*, Secchi depth, and DO

Index for sediment contamination is average of scores for metals, organics, and sediment toxicity

Index for benthos condition is the score for benthic community condition (benthic index)

The overall IEI is the average of all seven component scores

	Index is < 2; indicates good condition
	Index is 2 to 3.99; indicates moderate condition
	Index is ≥ 4 ; indicates poor condition

Fig. 7. MAIA-Estuaries Index of Environmental Integrity (IEI).

lar in concept to the Index of Biotic Integrity (IBI) developed by Karr (Karr, 1981; Karr and Chu, 1999). It was calculated directly from the report card, and included only the seven indicators with firm thresholds of impairment—TN, TP, and TOC were excluded. Scores were assigned to each cell according to its extent of degradation, and averaged to create indices for the severity of eutrophication, sediment contamination, and benthic degradation. An overall IEI was calculated by averaging all seven values. Because scores ranged from 0 to 6, the range was divided into three equal intervals (0–2, 2–4, and 4–6) to represent good, moderate, and poor condition.

This kind of index involves a number of assumptions, e.g., that its parameters accurately reflect the environmental state of estuaries, that the parameters are mutually independent and of equal weight, and that the index can be used on a wide range of geographic scales. These assumptions probably are not rigorously met. Furthermore, information is lost when data are simplified to a single value. For these reasons, the IEI is best used to highlight broad trends and to focus attention on the data used in constructing it. In this case, the index showed that: (1) the mid-Atlantic region was moderately impaired, primarily because of extensive eutrophication in most estuaries, Chesapeake Bay in particular; (2) Delaware Bay was in better condition than the tributaries in the Delaware Estuary; (3) the coastal bays were degraded by eutrophication, but otherwise showed little

indication of widespread degradation in their sediments or benthic communities; and (4) APES was moderately to severely impaired in all categories. In accord with MAIA's broader goals, this approach can also be used to summarize conditions in other resources (forests, streams, etc.). As such, it represents a step toward truly integrating the environmental assessment over broad regions and multiple resources (Paul, 2003).

3.6. Change in Estuarine condition over time

We close by illustrating another capability of probability-based environmental assessments—measuring environmental change over time. The study areas of EMAP-VP (1990–1993) and MAIA-Estuaries (1997–1998) overlapped in Chesapeake Bay and the Delaware Estuary. Subsystems in common in the two studies included the Delaware River and Delaware Bay in the Delaware Estuary; and the Chesapeake mainstem, and the Potomac, Rappahannock, and James rivers in Chesapeake Bay. Indicators measured by comparable methods in both studies included DO, metals and organics in sediments, sediment toxicity, and the benthic index. The change over time in estuarine condition was calculated as the difference in impaired area measured in the studies (Table 5), with positive values meaning increasing degradation. The difference was considered statistically significant if the two 95% confidence limits did not overlap (Cherry, 1996; Rahlfs, 1997; Austin and

Table 5

Environmental change between the 1990–1993 EMAP-Virginian Province (VP) and 1997–1998 MAIA-Estuaries programs

Estuary	Data source ^a	Metals in sediment ^b	Organics in sediment ^b	Sediment toxicity ^c	Benthic index ^d
Delaware River	EMAP-VP		2 ± 11.4%		
	MAIA-E		33.5 ± 9.6%		
	Δ		+31.5 ± 21%		
Chesapeake Bay overall	EMAP-VP	5.2 ± 3.1%		6.1 ± 3%	23.4 ± 4.8%
	MAIA-E	22 ± 5.4%		0.3 ± 0.3%	37 ± 5%
	Δ	+16.8 ± 8.5%		−5.8 ± 3.3%	+13.6 ± 9.8%
Chesapeake Bay mainstem	EMAP-VP	5.2 ± 4.2%		6.6 ± 5.8%	
	MAIA-E	26.8 ± 7.3%		0 ± 0%	
	Δ	+21.6 ± 11.5%		−6.6 ± 5.8%	
Potomac River	EMAP-VP	0.2 ± 0%			
	MAIA-E	28.6 ± 12.1%			
	Δ	+28.4 ± 12.1%			

Change was calculated as the difference in condition estimates, i.e., the percent estuarine area that exceeds the specified threshold of impairment. The difference was considered to be statistically significant if the 95% confidence limits of the EMAP-VP and MAIA-Estuaries estimates were non-overlapping. Positive values of change (Δ) designate a degradation of condition over time.

^a EMAP-VP: Environmental Monitoring and Assessment Program—Virginia Province 1990–1993. MAIA-E: Mid-Atlantic Integrated Assessment—Estuaries 1997–1998.

^b Percent estuarine area exceeding at least one ERM value.

^c Percent estuarine area with amphipod survival ≤ 80%.

^d Percent estuarine area with a benthic index ≤ 0.

Hux, 2002). In the Delaware River, fully one-third of the estuarine area was contaminated in 1997–1998, compared with only 2% in the earlier study. In Chesapeake Bay, 17% of the estuarine area had more ERM exceedances (22% and 28% in the mainstem and Potomac River, respectively). The condition of the benthic community worsened in Chesapeake Bay—14% more of the estuarine area had unfavorable benthic indexes in MAIA. Sediment toxicity improved slightly in Chesapeake Bay overall (6% of the area) and its mainstem (7% of the area). All comparable locations, indicators, and estimates of conditions involved in this comparison are presented in Appendix G of the MAIA Summary Report (USEPA, 2003).

Large increases in the percent area exceeding ERM limits were evident in Chesapeake Bay and Delaware River. We considered several factors that may have contributed to the apparent worsening of conditions. The proportion of shallower (potentially more contaminated) estuaries sampled in the EMAP and MAIA studies were examined by comparing the continuous distribution functions (CDFs) of water depth at stations sampled for sediment analysis in the two studies. The CDFs were similar, i.e., deep and shallow estuaries were sampled comparably; therefore, sampling bias was probably not a factor. We also investigated whether the greater density of stations in the MAIA study may have contributed to an increased incidence of ERM exceedances. In itself, the larger number of stations would not affect the outcome, since the weighting factors were proportionally smaller for the MAIA stations. However, it is possible that the higher station density, by chance, may have resulted in a wider range of measured contaminant concentrations (both higher and lower values). Since our analysis only reported increases above an upper threshold, more intensive monitoring could conceivably result in an apparent worsening of conditions. A detailed examination of the distribution of sediment contaminants over time in these regions and the factors affecting their interpretation is being conducted.

4. Summary

MAIA-Estuaries represents a significant evolution of and improvements to the original EMAP approach to sampling, choosing indicators, and reporting results. MAIA-Estuaries estimated estuarine condition with greater resolution than previously achieved. It quantitatively estimated the extent of eutrophication over broad regions by using a uniform set of indicators. It explored ways of distilling large quantities of technical data into forms useful to diverse audiences. The “Report Card” and Index of Integrity summarized the assessment and provided guidance on interpreting them. But perhaps the most important contribution of MAIA-

Estuaries was in moving away from the single-agency approach of environmental monitoring and toward partnerships. The extra effort of planning, sampling, and managing in MAIA-Estuaries was more than offset by the cost-effectiveness and expertise added by the collaboration. The resulting lessons have been incorporated into the National Coastal Assessment (NCA), which is a collaborative effort of EPA, other federal agencies, and all coastal states for assessing conditions in all US coastal waters (www.epa.gov/emap/nca/index.html).

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