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Relationships Between Benthic Community Condition, Water Quality, Sediment Quality, Nutrient Loads, and Land Use Patterns in Chesapeake Bay

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ABSTRACT: Associations between macrobenthic communities, measures of water column and sediment exposure, and measures of anthropogenic activities throughout the watershed were examined for the Chesapeake Bay, U.S. The condition of the macrobenthic communities was indicated by a multimetric benthic index of biotic integrity (B-IBI) that compares deviation of community metrics from values at reference sites assumed to be minimally altered by anthropogenic sources of stress. Correlation analysis was used to examine associations between sites with poor benthic condition and measures of pollution exposure in the water column and sediment. Low dissolved oxygen events were spatially extensive and strongly correlated with benthic community condition, explaining 42% of the variation in the B-IBI. Sediment contamination was spatially limited to a few specific locations including Baltimore Harbor and the Southern Branch of the Elizabeth River and explained about 10% of the variation in the B-IBI. After removing the effects of low dissolved oxygen events, the residual variation in benthic community condition was weakly correlated with surrogates for eutrophication—water column concentrations of total nitrogen, total phosphorus, and chlorophyll *a*. Associations between benthic condition and anthropogenic inputs and activities in the watershed were also studied by correlation analysis. Benthic condition was negatively correlated with measures of urbanization (i.e., population density, point source loadings, and total nitrogen loadings) and positively correlated with watershed forestation. Significant correlations were observed with population density and nitrogen loading below the fall line, but not above it, suggesting that near-field activities have a greater effect on benthic condition than activities in the upper watershed. At the tributary level, the frequency of low dissolved oxygen events and levels of sediment contaminants were positively correlated with population density and percent of urban land use. Sediment contaminants were also positively correlated with point source nutrient loadings. Water column total nitrogen concentrations were positively correlated with nonpoint nutrient loadings and agricultural land use while total phosphorus concentrations were not correlated with land use or nutrient loadings. Chlorophyll *a* concentrations were positively correlated with nitrogen and phosphorus concentrations in the water column and with agricultural land use but were not correlated with nutrient loads.

Introduction

Coastal seas, bays, lagoons, and estuaries have become increasingly degraded due to anthropogenic stresses (Nixon 1995). Relationships between land use, levels of nutrients and contaminants, and the condition of the biotic communities of receiving waters are well studied in freshwater ecosystems (Allan et al. 1997); few studies have addressed these relationships in estuarine ecosystems (Comeleo et al. 1996; Valiela et al. 1997).

Land use patterns in a watershed influence the delivery of nutrients, sediments, and contaminants into receiving waters through surface flow, groundwater flow, and atmospheric deposition (Correll 1983; Correll et al. 1987, 1992; Hinga et al. 1991; Lajtha et al. 1995; Jordan et al. 1997c). Increased nutrient loads are associated with high levels of agricultural and urban land use in both freshwater and coastal watersheds compared to forested watersheds (Klein 1979; Duda 1982; Ostry 1982; Novotny et al. 1985; Ustach et al. 1986; Valiela and Costa 1988; Benzie et al. 1991; Fisher and Oppenheimer 1991; Turner and Rabalais 1991; Correll et al. 1992; Jaworski et al. 1992; Lowrance 1992; Weiskel and Howes 1992; Balls 1994; Hall et al. 1994,

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TABLE 1. Response, exposure and watershed variables. B-IBI = Benthic Index of Biotic Integrity. DO = dissolved oxygen.

Category	Variable	Period	Number of Observations	Sources
Response	B-IBI	1984–1991	28,872	1, 2, 3
Exposure	Bottom water DO concentration	1984–1991	6,011	1, 2, 3, 4, 5
	Sediment contaminants	1984–1991	257	1, 2, 3, 6
	Total nitrogen	1984–1991	80,286	4, 5
	Total phosphorus	1984–1991	80,286	4, 5
	Chlorophyll *a*	1984–1991	80,286	4, 5
Watershed	Watershed Land Use (Forested, Agricultural, Urban)	1985	20	7
	Watershed population	1980, 1985, 1990	349	8
	Municipal point source total nitrogen and total phosphorus loadings	1985	521	9
	Municipal nonpoint source total nitrogen and total phosphorus loadings	1985	20	7

Sources: [1] Maryland Benthic Monitoring Program (J. A. Ranasinghe), [2] Virginia Benthic Monitoring Program (D. M. Dauer), [3] EPA Environmental Monitoring and Assessment Program (R. Latimer personal communication), [4] Maryland Department of Natural Resources (B. Micheal personal communication), [5] Chesapeake Bay Program Computer Center, [6] Eskin et al. 1996, [7] Linker and Allegre (1992), [8] NPA Data Services, Inc. (1991), [9] Chesapeake Bay Program (1988).

1996; Hopkinson and Vallino 1995; Nelson et al. 1995; Hill 1996; Allan et al. 1997; Correll 1997; Correl et al. 1997; Valiela et al. 1997; Verchot et al. 1997a,b; Gold et al. 1998). At smaller spatial scales, riparian forests and wetlands may ameliorate the effects of agricultural and urban land use (Johnston et al. 1990; Correll et al. 1992; Osborne and Kovacic 1993).

Aquatic biotic communities associated with watersheds with high agricultural and urban land use are generally characterized by lower species diversity, less trophic complexity, altered food webs, altered community composition, and reduced habitat diversity (Fisher and Likens 1973; Boynton et al. 1982; Conners and Naiman 1984; Malone et al. 1986, 1988, 1996; Mangum 1989; Howarth et al. 1991; Fisher et al. 1992; Grubaugh and Wallace 1995; Lamberti and Berg 1995; Roth et al. 1996; Correll 1997). High nutrient loads in coastal ecosystems result in increased algal blooms (Boynton et al. 1982; Malone et al. 1986, 1988; Fisher et al. 1992), increased low dissolved oxygen events (Taft et al. 1980; Officer et al. 1984; Malone et al. 1996), alterations in the food web (Malone 1992), and declines in valued fisheries species (Kemp et al. 1983; U.S. Environmental Protection Agency 1983). Sediment and contaminant loads are also increased in watersheds dominated by agricultural and urban development mainly due to storm-water runoff (Wilber and Hunter 1979; Hoffman et al. 1983; Medeiros et al. 1983; Schmidt and Spencer 1986; Beasley and Granillo 1988; Howarth et al. 1991; Vernberg et al. 1992; Lenat and Crawford 1994; Corbett et al. 1997).

Our study concerns Chesapeake Bay, the largest estuary in the United States. The Chesapeake Bay has a drainage basin of approximately 165,760 km^2 (U.S. Environmental Protection Agency 1983) and its watershed comprises over 150 rivers, streams, and creeks covering portions of six states and the District of Columbia. Six major tributaries, the Susquehanna, Potomac, Rappahannock, James, York, and Patuxent Rivers, contribute almost 90% of the total freshwater input to the Bay (U.S. Environmental Protection Agency 1983). Its economic importance is at least threefold: historically, it supported some of the most productive commercial fisheries in the world; it is a center of recreational and tourism activity; and it includes Hampton Roads and Baltimore, two of the largest ports in the United States.

Environmental conditions in the Chesapeake Bay and its tributaries have deteriorated significantly over the past 50 yr, resulting in declines in submerged aquatic vegetation, finfish and shellfish. These declines have been attributed primarily to increased eutrophication and toxic substances (U.S. Environmental Protection Agency 1983; Dauer et al. 1998). Coordinated bay-wide water quality and biological monitoring began in 1984, including abundance, biomass, and species diversity estimates of the plankton and benthic communities; concentrations of dissolved oxygen and nutrients in the water column; concentrations of chemical contaminants in the sediment; and measures of human activity in the watershed, such as population density, land use, and loadings of nutrients and toxics. Monitoring was one aspect of the Chesapeake Bay Agreements implemented between the U.S. Environmental Protection Agency, the State of Maryland, the Commonwealths of Pennsylvania and Virginia, and the District of Columbia in 1983 and 1987 to share responsibilities

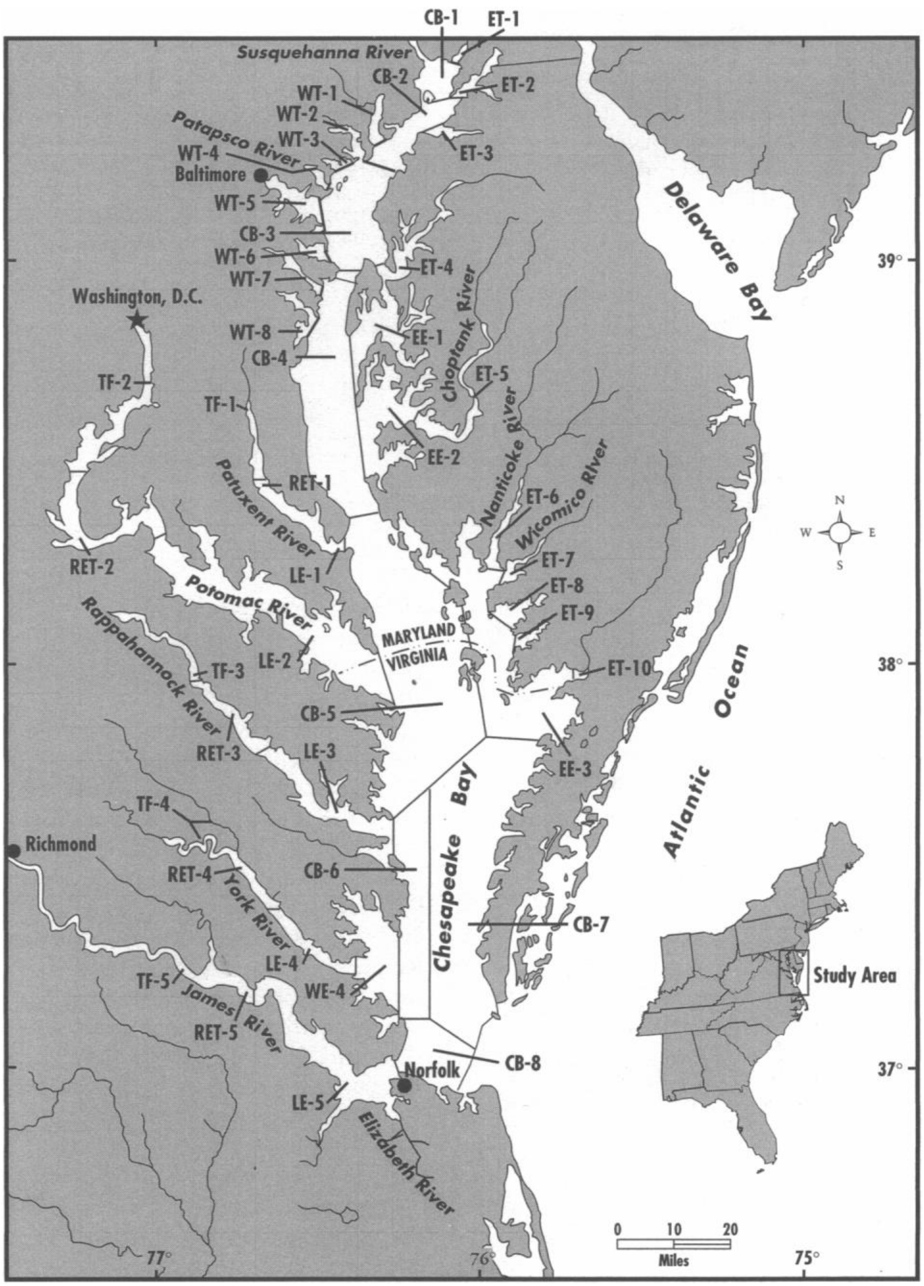

Fig. 1. Map of Chesapeake Bay showing Chesapeake Bay Program segments. The ten tributaries used for watershed analyses are indicated. Total length of the Chesapeake Bay depicted is approximately 300 km.

for a comprehensive, long-term program to restore the Bay's living resources.

Few studies of estuaries like Chesapeake Bay have attempted to explore relationships between biotic communities, their exposure to water-column and sediment pollution, and human activity throughout the watershed (Comeleo et al. 1996). Compared to freshwater systems, estuaries pose additional challenges due to the complexity and variability of physical and chemical factors (Hopkinson and Vallino 1995) such as tidal mixing and salinity gradients. The habitat specificity of biotic communities also hampers estuarine studies at large spatial scales. For example, the numbers and kinds of benthic organisms vary with salinity zone and sediment type, and confound efforts to assess relative condition and to associate causes and effects across habitat boundaries.

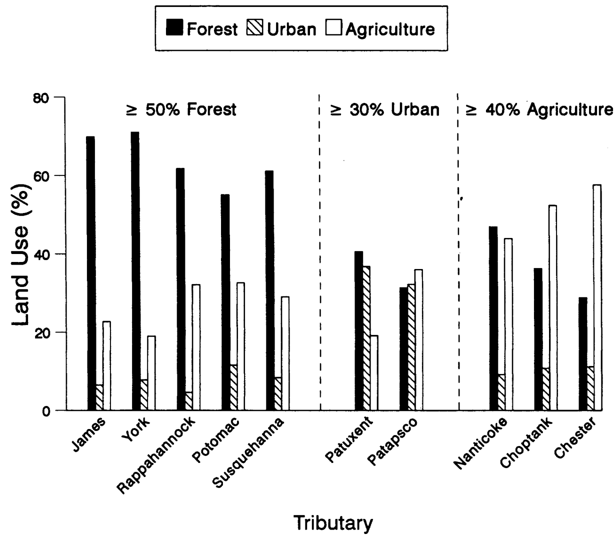

Fig. 2. Proportion of land use below the fall line (forested, urban and agricultural) for 10 tributaries of Chesapeake Bay.

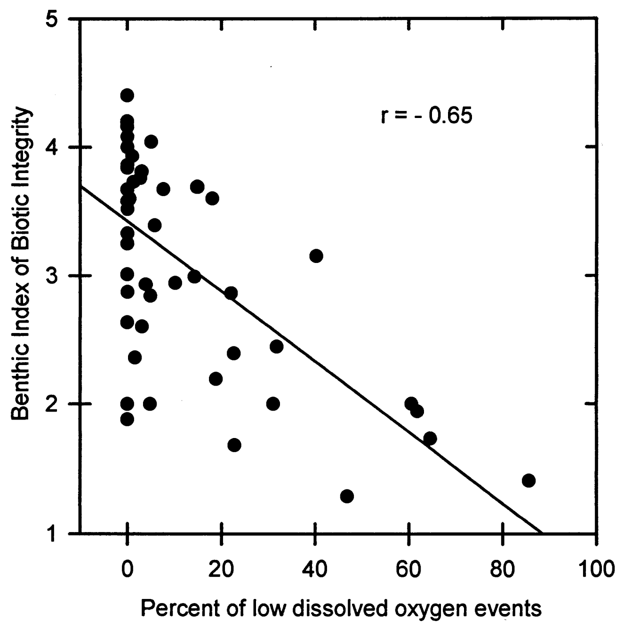

Fig. 3. Relationship of Benthic Index of Biotic Integrity to frequency of low dissolved oxygen events for each Chesapeake Bay Program segment (see Fig. 1). Percent of low dissolved oxygen events is the frequency of measurements of oxygen concentrations below 2 ppm during the index period of July 15 through September 30.

Our objective is to examine associations between the condition of benthic communities and measures of water quality, sediment quality, nutrient loads, and land use patterns in Chesapeake Bay. The condition of the macrobenthic communities of the Chesapeake Bay is measured by the Benthic Index of Biotic Integrity (Weisberg et al. 1997). Strong relationships have been found between freshwater benthic invertebrate community condition and land use patterns (Mangun 1989; Lenat and Crawford 1994; Grubaugh and Wallace 1995; Lamberti and Berg 1995), although few studies have examined estuarine benthic community condition in relation to watershed-level variables (Lerberg 1997).

Methods

Response, Exposure, and Watershed Variables

Three kinds of indicators of environmental condition were identified from available Chesapeake Bay monitoring programs: a biological response variable, exposure variables, and watershed variables. The biological response variable was the Benthic Index of Biotic Integrity (B-IBI) developed for macrobenthic communities of the Chesapeake Bay (Weisberg et al. 1997). The index defines expected conditions at reference sites relatively free of anthropogenic stress, and then assigns categorical values for various descriptive metrics by comparison with observations at these reference sites. The result is a multi-metric index of biotic condition, frequently referred to as an index of biotic integrity (IBI). The analytical approach was similar to the one Karr et al. (1986) used to develop comparable indices for freshwater fish communities. Selection of benthic community metrics and metric scoring thresholds were habitat-dependent but by using categorical scoring comparisons between habitat types were possible. A six-step procedure was used to develop the index: acquire and standardize data sets from a number of monitoring programs; temporally and spatially stratify data sets to identify seasons and habitat types; identify reference sites; select benthic community metrics; select metric thresholds for scoring; and validate the index with an independent data set (Weisberg et al. 1997). The B-IBI developed for Chesapeake Bay is based upon subtidal, unvegetated, infaunal macrobenthic communities. Hard-bottom communities, e.g., oyster beds, were not sampled as part of the monitoring program because the sampling gears could not obtain adequate samples to characterize the associated infaunal communities. Infaunal communities associated with submerged aquatic vegetation (SAV) were not avoided, but were rarely sampled due to the limited spatial extent of SAV in Chesapeake Bay.

Only macrobenthic data sets based on processing with a sieve of 0.5-mm mesh aperture and identified to the lowest possible taxonomic level were used. A data set of over 2,000 samples collected from 1984 through 1994 was used to develop, calibrate and validate the index (see Table 1 in Weisberg et al. 1997). Because of inherent temporal

TABLE 2. Results of correlation analysis between Benthic Index of Biotic Integrity values and exposure variables. r = Pearson correlation coefficient, p = probability level, n = number of replicates. Analyses were performed with and without low dissolved oxygen effect. DO = dissolved oxygen. ER-M = effects range-median of Long et al. (1995). ER-L = effects range-low of Long et al. (1995). TN, TP = water column concentrations of total nitrogen and total phosphorus. Chlorophyll *a* measured in water column.

	Correlation Using Entire Study Means			Correlations With Residuals After Removing Low DO Effects		
Exposure Variable	r	p	n	r	p	n
Percentage of summer bottom-water DO measurements <2 ppm	−0.652	0.0001	49			
No. of chemicals for which the segment mean concentration >ER-M	−0.314	0.049	40	−0.430	0.006	40
No. of chemicals for which the segment mean concentration >ER-L	−0.268	0.095	40	−0.265	0.099	40
Mean TN	−0.131	0.402	43	−0.390	0.010	43
Mean TP	−0.060	0.704	43	−0.381	0.012	43
Mean chlorophyll *a*	−0.086	0.585	43	−0.302	0.005	43

sampling limitations in some of the data sets, only data from the period of July 15 through September 30 were used to develop the index. A multivariate cluster analysis of the biological data was performed to define habitat types. Salinity and sediment type were the two important factors defining habitat types and seven habitats were identified—tidal freshwater, oligohaline, low mesohaline, high mesohaline sand, high mesohaline mud, polyhaline sand, and polyhaline mud habitats (see Table 5 in Weisberg et al. 1997).

Reference sites were selected as those sites which met all three of the following criteria: no sediment contaminant exceeded Long et al.'s (1995) effects range-median (ER-M) concentration, total organic content of the sediment was less than 2%, and bottom dissolved oxygen concentration was consistently high.

A total of 11 metrics representing measures of species diversity, community abundance and biomass, species composition, depth distribution within the sediment, and trophic composition were used to create the index (see Table 2 in Weisberg et al. 1997). The habitat-specific metrics were scored and combined into a single value of the B-IBI. Thresholds for the selected metrics were based on the distribution of values for the metric at the reference sites. Data used for validation were collected between 1992 and 1994 and were independent of data used to develop the index. The B-IBI classified 93% of the validation sites correctly (Weisberg et al. 1997). The B-IBI data used in the present study overlapped with the original data set used to develop the index. Less than 15% of the B-IBI data used in the present study were also used to develop and validate the B-IBI. In this study segments with B-IBI values >3.00 are characterized as having healthy benthic communities, segments with B-IBI values between 2.99 and 2.00 as degraded benthic communities and segments with B-IBI values <2.00 as severely degraded. These categories are used in annual characterizations of the condition of the benthos in the Chesapeake Bay (Ranasinghe et al. 1994b; Dauer et al. 1998; Ranasinghe et al. 1998).

Exposure variables, the second kind of indicator, are measures of the occurrence or magnitude of physical, chemical, or biological stress. Five exposure variables were selected: bottom water dissolved oxygen concentrations; sediment contaminant concentrations; and water column concentrations of total nitrogen, total phosphorus, and chlorophyll *a* (chl *a*) (Table 1). Dissolved oxygen was selected because of the documented effects of hypoxia on benthic communities of the Chesapeake Bay (Holland et al. 1977, 1987; Pihl et al. 1991; Dauer et al. 1992, 1993; Dauer 1993; Diaz and Rosenberg 1995). Hypoxia is most frequently associated with deeper areas (below the pycnocline) but wind-driven seiching can bring oxygen-depleted bottom waters over adjacent shallow areas (Tuttle et al. 1987; Breitburg 1990). Contaminants were selected because they present diverse stresses to benthic communities and human health (Baker 1980a,b; National Research Council 1989), and have been previously shown to affect benthic community structure in Chesapeake Bay (Dauer 1993; Dauer et al. 1993). Sediment contaminants are potentially toxic substances and in this study included trace metals (Ag, As, Cd, Cr, Cu, Hg, Ni, Pb, Zn), total polycyclic aromatic hydrocarbons, total polychlorinated biphenyls, and the pesticide DDT. Water column concentrations of nitrogen, phosphorus, and chl *a* were selected as indicators of eutrophication. Levels of chl *a* can be related to patterns of nutrients in Chesapeake Bay (Harding and Perry 1997) and chlorophyll levels are considered the best indicator of nitrogen and phosphorus enrichment in Chesapeake Bay (Harding 1994). Benthos may benefit from higher productivity at low levels of eutrophication but suffer reductions in diversity and function at higher levels of enrichment (Pear-

TABLE 3. Area-weighted values of response and exposure variables for tributaries. Data for the Susquehanna River are drawn from Bay segment CB-1. B-IBI = Benthic Index of Biotic Integrity. DO = dissolved oxygen. ER-L = effects range-low of Long et al. (1995). TN, TP = total nitrogen, total phosphorus concentration in water column.

Tributary	Variable					
	Mean B-IBI Value	Bottom % DO obs <2 ppm	No. of Contaminants >ER-L	Mean TN ($mg\ l^{-1}$)	Mean TP ($mg\ l^{-1}$)	Mean chlorophyll *a* ($\mu g\ l^{-1}$)
James	3.35	0.74	0.8	0.71	0.077	13.67
York	3.83	0.30	ND	0.79	0.105	41.65
Rappahannock	2.76	6.82	1.0	0.68	0.049	13.59
Potomac	2.85	20.81	1.6	0.54	0.033	4.52
Patuxent	2.98	16.07	3.0	0.37	0.031	5.30
Patapsco	1.77	18.49	10.0	0.51	0.024	8.61
Susquehanna	3.84	0.00	0.0	1.60	0.048	8.60
Chester	2.87	5.30	0.0	2.19	0.131	37.05
Choptank	3.26	5.82	0.0	1.66	0.089	15.62
Nanticoke	2.63	0.00	0.0	2.18	0.068	17.27

son and Rosenberg 1978; Diaz and Rosenberg 1995).

Watershed variables, the third category of indicators, are measures of human activity or natural phenomena that potentially affect estuarine communities indirectly by causing changes in exposure variables. The selected watershed variables included land use patterns, human population density, and point- and nonpoint source loadings of nitrogen and phosphorus (Table 1). Although point- and nonpoint source nutrient loads can be managed, excessive precipitation or drought may overwhelm management actions.

We used data from the Chesapeake Bay from 1984 to 1991. Data were identified by reviewing annual reports for each component of the Chesapeake Bay Water Quality Monitoring Program, interviewing principal investigators of the Water Quality Monitoring Program, and reviewing the Chesapeake Bay Basin Monitoring Program Atlas compiled by the U.S. Environmental Protection Agency Chesapeake Bay Program Office (Heasly et al. 1989). In addition, two computerized databases, the CHESSIE database maintained by the U.S. Environmental Protection Agency Chesapeake Bay Program Office and the Nonpoint Source Electronic Bulletin Board maintained by the U.S. Environmental Protection Agency Nonpoint Source Information Exchange, were searched for information about ongoing projects. Data sets were acquired if they included measures relevant to our objectives and if the data were collected between 1984 and 1991. Data sets that included annual observations over the entire period were preferred, but data sets consisting of observations for only a few years were included if data with long-term annual time series were not available. Greater detail

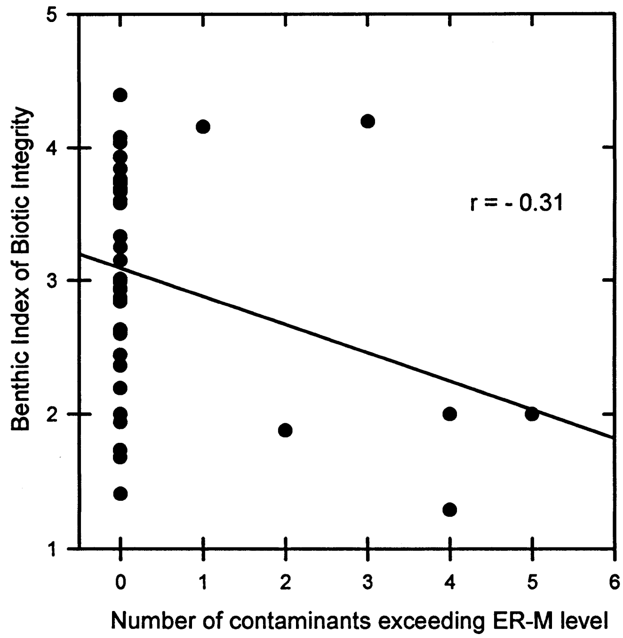

Fig. 4. Relationship of Benthic Index of Biotic Integrity to sediment contamination for each Chesapeake Bay Program segment (see Fig. 1). Sediment contamination is measured by the number of contaminants that exceed ER-M levels of Long et al. (1995).

concerning the process of identifying, acquiring and standardizing data for this study can be found in Chaillou et al. (1992) and Ranasinghe et al. (1994b).

Segmentation of Chesapeake Bay and its Tributaries

Values of the B-IBI and exposure variables were calculated for segments of the Chesapeake Bay and its tributaries (Fig. 1). Segmentation was originally developed to stratify the Bay into regions with similar salinity and hydrographic characteristics. We used a slightly modified version of the Chesapeake Bay Program (CBP) segmentation scheme (Heasly et al. 1989) to aggregate each kind of data. The first modification of the CBP segmentation scheme was to divide segments into "deep" (below pycnocline) and "shallow" (above pycnocline) subdivisions if salinity, dissolved oxygen, or temperature differed considerably between the surface and bottom during summer (data collected between June and September). This subdivision of segments was done to preserve within-segment, depth-related differences in exposure to hypoxia. Segments were subdivided if the difference between surface and bottom mean summer values was greater than 2‰ for salinity, 2 ppm for dissolved oxygen concentration, or 4°C for temperature. The boundary between the shallow and deep subdivisions of a seg-

TABLE 4. Correlation of area-weighted B-IBI values with total watershed, above-fall line, and below-fall line watershed variables. Pearson correlation coefficients, probability values, and number of replicates are presented for each watershed variable. Population density was measured in individuals acre^{-1} of tributary watershed. Nutrient loading was measured in g d^{-1} acre^{-1} of tributary watershed.

Watershed Variable	Total Watershed	Above Fall Line	Below Fall Line
Population density per unit area	−0.701	−0.283	−0.664
	0.024	0.587	0.051
	10	6	9
% Area under Agriculture	−0.330	−0.691	−0.271
	0.351	0.128	0.480
	10	6	9
% Forested area	0.623	0.566	0.549
	0.054	0.242	0.125
	10	6	9
% Urban area	−0.514	−0.241	−0.407
	0.129	0.646	0.277
	10	6	9
Total point and nonpoint source nitrogen loadings per unit area	−0.687	−0.197	−0.693
	0.03	0.708	0.038
	10	6	9
Point source nitrogen loadings per unit area	−0.720	−0.252	−0.678
	0.019	0.630	0.045
	10	6	9
Nonpoint source nitrogen loadings per unit area	−0.258	−0.086	−0.287
	0.472	0.871	0.454
	10	6	9
Total point- and nonpoint source phosphorus loadings per unit area	−0.450	−0.232	−0.425
	0.129	0.658	0.254
	10	6	9
Point source phosphorus loadings per unit area	−0.703	−0.221	−0.535
	0.023	0.674	0.138
	10	6	9
Nonpoint source phosphorus loadings per unit area	−0.265	−0.186	−0.270
	0.460	0.725	0.482
	10	6	9

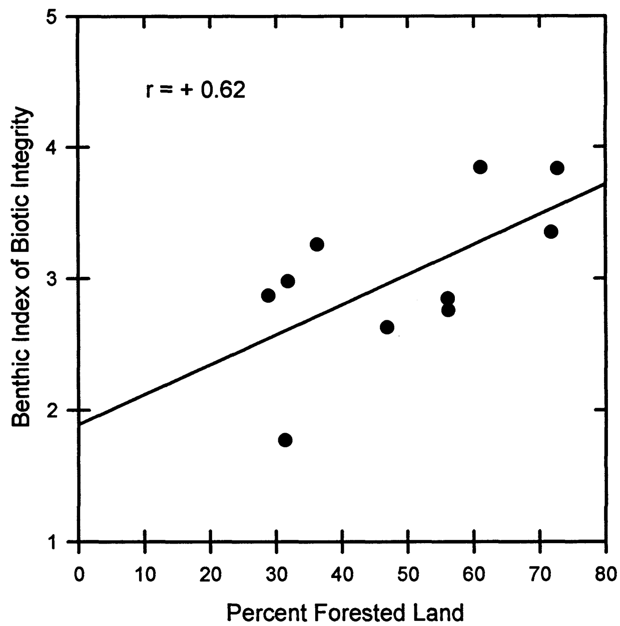

Fig. 5. Relationship of Benthic Index of Biotic Integrity to percent of forested land cover of watersheds of ten tributaries of the Chesapeake Bay (See Table 3).

ment was defined as the average of the pycnocline and thermocline depths. The following segments were divided into deep and shallow subdivisions: CB-3, CB-4, CB-5, CB-6, CB-7, CB-8 (Mainstem Bay); WT-5 (Patapsco River); ET-4 (Chester River); ET-5 (Choptank River); RET-1 (Middle Patuxent River); LE-1 (Lower Patuxent River); RET-2 (Middle Potomac River); LE-3 (Lower Rappahannock River); LE-4 (Lower York River); and WE-4 (Mobjack Bay). For details of the actual depth separating deep and shallow classes see Ranasinghe et al. (1994b). The second modification was to create a separate segment for the Southern Branch of the Elizabeth River, which was originally part of segment LE-5 (the Lower James River). Although most CBP segments are relatively homogenous with respect to geographic features and salinity regimes, the sediments of the Southern Branch of the Elizabeth River contain higher concentrations of contaminants than other lower James River sediments (Alden et al. 1988; Dauer 1993; Dauer et al. 1993). These modifications resulted in the data being divided into 61 segments for analysis.

For the B-IBI, nutrients, and chlorophyll, segment condition was characterized by the mean of all values for measurements at all sites within each segment-depth subdivision. For dissolved oxygen, segment condition was summarized as the percentage of summer (July 15–September 30) measurements with concentrations below 2 ppm. Benthic organisms are known to respond negatively to concentrations below this level (Diaz and Rosenberg 1995). Sediment contaminants were expressed as the number of chemicals for which average concentrations exceeded the effects range-low (ER-L) and effects range-median (ER-M) values of Long et al. (1995). ER-L values represent chemical concentrations at which biological responses are first seen and ER-M values represent concentrations at which biological responses are expected to occur. These values were selected because they represent the best available summary of chemical concentrations in terms of expected biological effects. To ensure validity of comparison among Bay segments, contaminant data sets were included in the analysis only if they contained measurements for a wide array of both metals and organic chemicals.

Association Between Benthic Response, Exposure and Watershed Variables

Associations between benthic response (the B-IBI) and exposure measures were evaluated using correlation analysis to test for linear relationships. Correlation analyses were conducted using each of the segment-depth subdivisions as an aggregation level for pairing benthic response and exposure variables.

Associations between benthic response measures and watershed variables were analyzed also using correlation analysis; however, the spatial scale of aggregation was different. Instead of using Bay segments, watershed variables were summarized for each of ten tributaries for which watershed level data were available (the James, York, Rappahannock, Potomac, Patuxent, Patapsco, Susquehanna, Chester, Choptank, and Nanticoke Rivers). Watershed data were aggregated for tributaries because they are measures of activities and phenomena taking place throughout tributary watersheds and because watershed variables were not measured at scales fine enough to quantify particular kinds of stress within segments of tributaries. The ten tributaries of the Chesapeake Bay for which both benthic response data and watershed-level variables were available included highly developed urban watersheds, extensively agricultural watersheds, largely forested, and mixed watersheds (Fig. 2).

Benthic response and exposure measures had to be recalculated at the tributary level of aggregation to identify correlations with watershed variables. This was accomplished by calculating an area-weighted mean for all segment-depth subdivisions within each tributary. The tributary mean was calculated as the average of the values used to characterize each subdivision and weighted by the area of the subdivision's substratum. Areas used as weighting factors for non-subdivided segments were obtained from Cronin (1971). Areas for the deep portions of subdivided segments were calculated from Cronin and Pritchard (1975) as the 1-m-thick layer of water at the deep-shallow boundary depth (see Ranasinghe et al. 1994b); areas for shallow subdivisions were obtained by subtracting the deep subdivision area from the total segment area.

Several procedures were performed to aggregate watershed data to the tributary scale. Different approaches were necessary for land use and nonpoint source loadings, point source loadings, and population estimates due to the forms in which those data were available. Estimates of tributary watershed area, land use, and nonpoint source nutrient loadings for 1985 were based on results of the Chesapeake Bay Program's Watershed Model (Linker and Allegre 1992). Results for model segments corresponding to U.S. Geological Survey (USGS) hydrologic units were summed for areas above and below the fall line in each tributary. The nonpoint source loadings used for this study were sums of watershed model results calculated from animal units and land use. All nonpoint source loadings were expressed as g d^{-1} $acre^{-1}$ of tributary watershed.

Point source loadings for 1985 from municipal dischargers in each tributary were obtained from the Atlas85 database (Chesapeake Bay Program 1988). Average annual total phosphorus and total nitrogen discharge concentrations were converted to loadings for each facility located in each of the ten tributaries. Facility totals were summed for model segments above and below the fall line. All point source loadings were expressed as g d^{-1} $acre^{-1}$ of tributary watershed.

Population estimates for model segments above and below the fall line in each tributary were calculated assuming that populations were distributed evenly across counties and cities. County and city population estimates for 1985 were obtained from NPA Data Services, Inc. (1991), normalized for the proportion of county or city area within each model segment, and summed for above- and below-fall line areas. The areas of each county and city contained within model segments were obtained from the Chesapeake Bay Watershed Model (Linker and Allegre 1992). Population density estimates were expressed as individuals $acre^{-1}$ of tributary watershed.

For each of the watershed variables, above-fall line, below-fall line, and total watershed values were calculated for each tributary, except for the Susquehanna River, which has no below-fall line land area comparable to the below-fall line areas defined for the other tributaries in this study; and for the Patapsco, Chester, Choptank, and Nanticoke Rivers, which have small above-fall line watersheds and for which separate above-fall line estimates were unavailable. Values were expressed per acre of watershed land area of each tributary.

Results

Associations Between Benthic Community Condition, Exposure, and Watershed Variables

Benthic community condition as estimated by the B-IBI was negatively correlated with exposure to low dissolved oxygen (Table 2; Fig. 3). Exposure to low dissolved oxygen, as estimated by the percentage of measurements less than 2 ppm, accounted for 42.6% of the variation in mean B-IBI values for segment-depth subdivisions for the entire Chesapeake Bay watershed. Low dissolved oxygen events were spatially widespread and occurred in 32 of the 61 Baywide segments and in all of the selected tributaries except the Nanticoke River and the Susquehanna River (Table 3).

Benthic community condition was also negative-

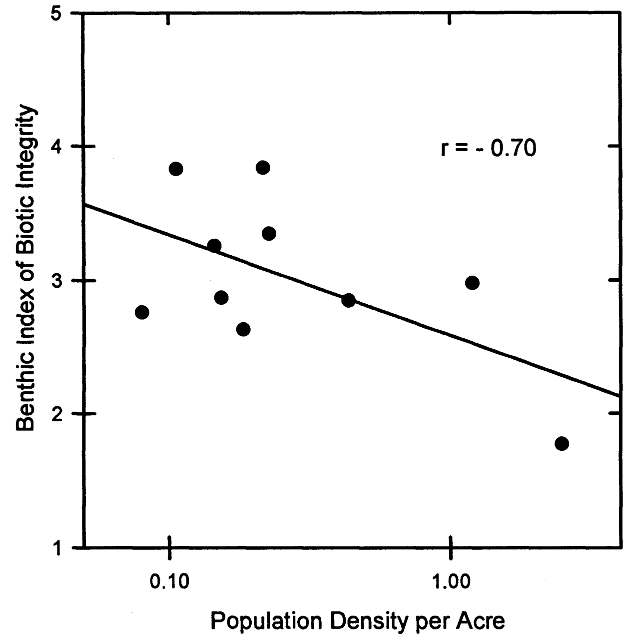

Fig. 6. Relationship of Benthic Index of Biotic Integrity to population density per unit area of watersheds of ten tributaries of the Chesapeake Bay (See Table 3).

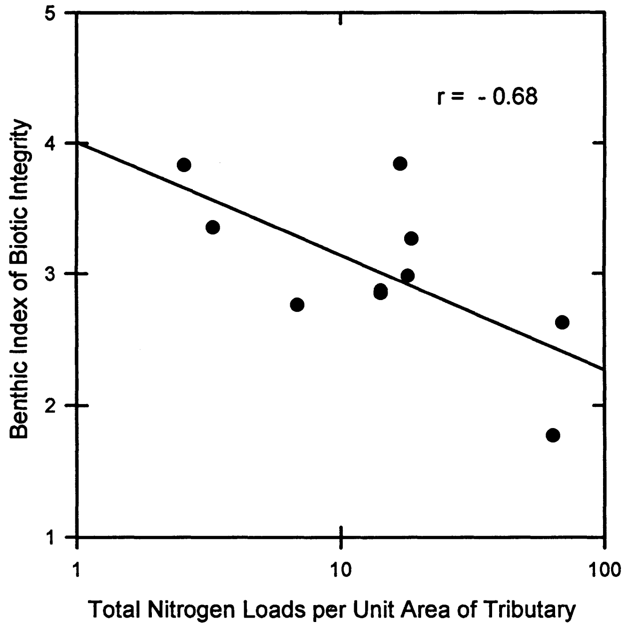

Fig. 7. Relationship of Benthic Index of Biotic Integrity to total nitrogen loads per unit area of watersheds of ten tributaries of the Chesapeake Bay.

ly correlated with exposure to sediment contaminants (Table 2; Fig. 4), but the correlation explained only about 10% of the variation. Only seven of the 61 segments had any contaminants that exceeded ER-M levels: the mainstem segment CB-2, the Middle River (WT-3), the Back River (WT-4), the deep and shallow segments of the Patapsco River (WT-5), the upper Potomac River (TF-2) and the Elizabeth River (SB).

The three measures of eutrophication used in this study (water column concentrations of total nitrogen, total phosphorus, and chl *a*) were not correlated with the spatial distribution of degraded benthos (Table 2). Because the relationship to dissolved oxygen was so strong and spatially extensive, additional correlation analyses were conducted on residual values of the B-IBI after removing the effect of dissolved oxygen events using a regression analysis. The residuals of the B-IBI were significantly correlated with all of the measures of contaminant and eutrophication exposure, except the numbers of contaminants for which the average concentration exceeded the ER-L value (Table 2). Water column nutrient and chl *a* levels each accounted for only 10–15% of the residual variation in benthic community condition.

At the total watershed level, benthic community condition was marginally, positively correlated with percent forested land area (Table 4; Fig. 5). The B-IBI was negatively correlated with indicators of urbanization (i.e., population density, point source loadings, and total nitrogen loadings; Table 4). The correlations with indicators of urbanization were due to one or two tributaries with high values. The correlation with population density (Fig. 6), total nitrogen loadings (Fig. 7), and point source nutrient loadings were driven by the Patapsco River. Without the Patapsco River the relationships become non-significant.

Associations Between Exposure and Watershed Variables

The ten tributaries of the Chesapeake Bay for which both watershed and benthic response data were available drained a range of watersheds, including highly developed urban watersheds, extensively agricultural watersheds, largely forested watersheds, and mixed watersheds (Fig. 2). The most heavily urbanized tributaries were the Patapsco, Patuxent, and Potomac Rivers which drain major metropolitan areas including the District of Columbia and Baltimore, Maryland (Fig. 1). The three eastern shore tributaries, the Chester, Choptank, and Nanticoke Rivers had the highest proportion of agricultural land use. The Susquehanna, Rappahannock, York, and James Rivers had the least developed watersheds and the highest proportion of forested area. The Susquehanna and York Rivers had the best benthic condition and the Patapsco River had the poorest benthic condition (Table 3).

Measures of urban and agricultural stress were

TABLE 5. Correlation of area-weighted exposure variables with watershed variables. Pearson correlation coefficients, probability values, and number of replicates are presented for each watershed variable by exposure variable combination. DO = dissolved oxygen. ER-L = effects range-low of Long et al. (1995). TN, TP = total nitrogen, total phosphorus concentration in water column.

Watershed Variables	% Bottom DO obs <2 ppm	No. of Contaminants >ER-L	Mean TN ($mg\ l^{-1}$)	Mean TP ($mg\ l^{-1}$)	Mean Active Chlorophyll *a* ($\mu g\ l^{-1}$)
Population density per unit land area	0.679	0.977	−0.473	−0.593	−0.381
	0.031	0.001	0.167	0.071	0.278
	10	9	10	10	10
% Area under agriculture	−0.059	−0.219	0.757	0.446	0.686
	0.871	0.572	0.011	0.196	0.029
	10	9	10	10	10
% Forested area	−0.440	−0.385	−0.328	−0.023	−0.341
	0.204	0.307	0.355	0.949	0.366
	10	9	10	10	10
% Urban area	0.685	0.742	−0.424	−0.517	−0.353
	0.029	0.022	0.222	0.126	0.317
	10	9	10	10	10
Total nitrogen loadings per unit land area	0.127	0.479	0.302	−0.278	−0.025
	0.726	0.192	0.397	0.437	0.946
	10	9	10	10	10
Point source nitrogen loadings per unit land area	0.529	0.970	−0.360	−0.466	−0.255
	0.116	0.001	0.307	0.174	0.477
	10	9	10	10	10
Nonpoint-source nitrogen loadings per unit land area	−0.240	−0.212	0.663	0.032	0.187
	0.451	0.583	0.037	0.929	0.603
	10	9	10	10	10
Total phosphorus loadings per unit land area	−0.133	0.052	0.546	−0.076	0.116
	0.713	0.894	0.103	0.835	0.750
	10	9	10	10	10
Point source phosphorus loadings per unit land area	0.488	0.963	−0.343	−0.460	−0.254
	0.152	0.001	0.331	0.181	0.479
	10	9	10	10	10
Nonpoint-source phosphorus loadings per unit land area	−0.223	−0.216	0.650	0.049	0.322
	0.535	0.577	0.042	0.892	0.365
	10	9	10	10	10

each correlated with a subset of the exposure variables (Table 5). Frequency of hypoxia and sediment contamination were both correlated with urban variables. Hypoxia was correlated with population density and percent urban area in the watershed (Fig. 8). Sediment contamination was strongly correlated with population density and point source nitrogen and phosphorus loadings and moderately correlated with urban land use (Table 5; Fig. 9).

Mean annual concentrations of chl *a* and total nitrogen were both correlated with agricultural land use (Table 5; Figs. 10 and 11). Total nitrogen concentration was also correlated with nonpoint source nutrient loads. These correlations are due to the three Eastern Shore tributaries, the Chester, Choptank and Nanticoke Rivers, which have the highest agricultural land use, nonpoint source nutrient loadings, nitrogen concentrations, and chl *a* concentrations (Table 3).

Discussion

Low Dissolved Oxygen Events

Benthic community condition in Chesapeake Bay was most strongly related to the frequency of low dissolved oxygen events (Table 2; Fig. 3). These were spatially widespread, occurring in 32 of the 61 Baywide segments used in this study (Fig. 1). Severely degraded benthic communities and very low oxygen concentrations occurred throughout the deep mesohaline regions of the mainstem of the Bay and the Patapsco, Potomac, and Rappahannock Rivers while the healthiest benthic communities occurred in polyhaline regions where low dissolved oxygen events are rare. These results are consistent with previous characterizations of low dissolved oxygen events and benthic community effects within Chesapeake Bay (Holland et al. 1977, 1987; Pihl et al. 1991; Dauer et al. 1992, 1993; Dauer 1993; Diaz and Rosenberg 1995). Mesohaline regions of temperate partially-stratified estuaries may be naturally hypoxic due to circulation patterns that trap organic matter in bottom waters (Malone et al. 1988; Malone 1992) and high rates of deposition of particulate organic matter to the benthos (Kemp and Boynton 1992; Malone 1992). Presumably oligohaline areas in Chesapeake Bay are flushed well enough to carry the biochemical oxygen demand created by the high nutrients and chlorophyll downstream and trap it in the meso-

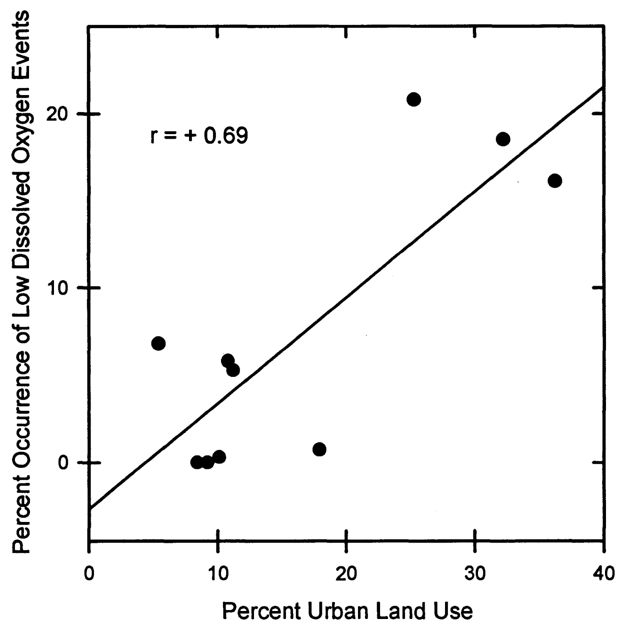

Fig. 8. Relationship of frequency of low dissolved oxygen events during the index period of July 15 to September 30 to percent of urban land use of watersheds of ten tributaries of the Chesapeake Bay (See Table 3).

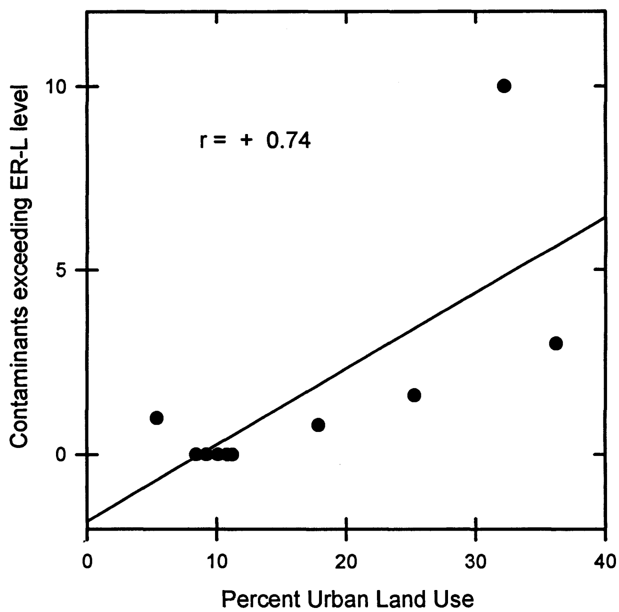

Fig. 9. Relationship of sediment contaminant levels as measured by ER-L levels (Long et al. 1995) to percent urban land use of watersheds of ten tributaries of the Chesapeake Bay (See Table 3).

haline mixing zones. Oxygen stress in polyhaline areas of the lower Bay is presumably ameliorated by strong vertical mixing and exchange with well-oxygenated ocean waters. Clearly, benthic communities below the pycnocline in mesohaline waters are the most degraded in the Bay (Holland et al. 1987; Dauer et al. 1992).

The large areal extent and high frequency of low dissolved oxygen events in Chesapeake Bay has been attributed primarily to increased eutrophication driven by high nutrient loads (U.S. Environmental Protection Agency 1983). Our results demonstrate that low dissolved oxygen events are correlated with measures of urbanization (population density and urban land use; Fig. 8) but not with nutrient loads (Table 5). Although urban areas undoubtedly contribute to hypoxia through the biological oxygen demand of urban runoff, sewage, and point source nutrients, the eight tributaries that experienced hypoxia (Table 3) were all potentially exposed to hypoxic subpycnocline waters entering the tributaries from the central mainstem of the Bay (Boicourt 1992). The deep water portions of segments CB-3, CB-4, and CB-5 in the mainstem of Chesapeake Bay (Fig. 1) had high frequencies of low dissolved oxygen events, 40%, 85%, and 64%, respectively. The lack of relationships of low dissolved oxygen events to nutrient loads is not an unexpected result due to potentially distant spatial links between locations of nutrient inputs and regions of hypoxia or anoxia. In addition, vertical mixing of the water column, either due to shallow water depths of some tributaries or strong gravitational and tidal circulation (Kuo and Neilson 1987) will prevent water column stratification and

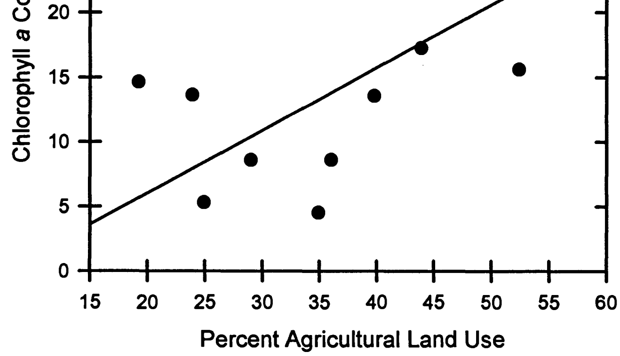

Fig. 10. Relationship of chlorophyll *a* levels to percent agricultural land use of watersheds of ten tributaries of the Chesapeake Bay (See Table 3). Chlorophyll concentrations are $\mu g\ l^{-1}$.

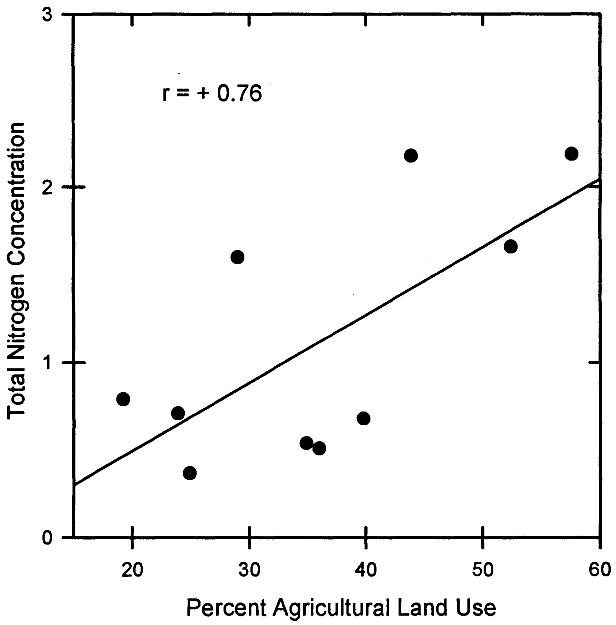

Fig. 11. Relationship of mean total nitrogen concentration to percent agricultural land use at the tributary level of data aggregation (See Table 3). Total nitrogen concentrations are mg l^{-1}.

subsequent low dissolved oxygen events driven by eutrophication.

Sediment Contaminants

Benthic community condition was negatively related to sediment contaminant levels (Table 2; Fig. 4). Sediment contaminant effects on macrobenthic communities of Chesapeake Bay are well documented (Alden et al. 1988; Dauer 1993; Dauer et al. 1993, 1998; Ranasinghe et al. 1994b); however, the effects on benthic communities are spatially limited. Only a few Bay segments, for example the segments containing the Elizabeth River, the Back River, and the Patapsco River, have exceptionally high concentrations of contaminants and severely degraded benthic communities (Alden et al. 1988; Dauer 1993; Dauer et al. 1993, 1998). The deep regions of the Patapsco River have both high levels of contaminants and frequent low dissolved oxygen events (Ranasinghe et al. 1994b). The remainder of the Bay showed little relationship between the presence of contaminants and the condition of the benthic communities. Comeleo et al. (1996) found that levels of metals and organic contaminants in estuarine sediments of Chesapeake Bay were best predicted by small-scale land use (less than 10 km from the sampling location) than by land use patterns at the level of entire watersheds. From a management perspective, these findings suggest that problems caused by contaminants are localized. However, the ecological effects of chronic levels of multiple contaminants in estuaries are not well understood (Fulton et al. 1993) and may not be detected at the spatial scales of this study.

At the watershed level sediment contamination in our study was correlated with measures of urbanization (Fig. 9) and point source nutrient loads (Table 5). Sources of estuarine sediment contamination have historically been urban point sources (e.g., sewage and industrial outfalls) and, to a lesser degree, urban runoff and atmospheric deposition (U.S. Environmental Protection Agency 1983; Vernberg et al. 1992). The correlations of contaminants with proportion of urban area and population density per unit area were driven by the responses observed in the Patapsco and Patuxent Rivers, which are highly urbanized and have known historical sources of contamination.

Eutrophication Variables

Benthic community condition was only weakly related to surrogate measures of eutrophication (water column concentrations of total nitrogen, total phosphorus and chl *a*) and only with residual B-IBI values after the effects of low dissolved oxygen events were removed (Table 2). These results probably reflect the minimal effect of eutrophication on the benthos in the absence of low dissolved oxygen events. Due to the complex interactions between water flow, tidal mixing, and retention times (Day et al. 1989; Boicourt 1992; Eyre 1994), regions of nutrient enrichment, increased phytoplankton biomass or primary productivity, increased deposition of particulate organic matter, lowered dissolved oxygen concentrations, and degraded benthos are often temporally and spatially disconnected, preventing strong associations between eutrophication exposure variables and benthic condition. The use of annual mean values for chlorophyll concentration and benthic metrics measured only during the summer (July 15 through September 30) may increase our ability to link benthic condition to dissolved oxygen stress but decrease the link to chlorophyll production. For example, Kemp and Boynton (1992) found a significant correlation between annual mean benthic polychaete biomass and spring chlorophyll levels, but not with summer chlorophyll levels. The pattern they observed was presumably driven by the importance of spring deposition events to recruitment and survivorship of the macrobenthos (Marsh and Tenore 1990). Over large spatial scales, short-term nutrient enrichment can enhance benthic production by increasing phytoplankton biomass and the amount of organic matter reaching the bottom as food. Over longer time periods, excess organic matter decomposes, creating low dissolved oxygen conditions and a degraded benthic community (Pearson and Rosenberg 1978; Diaz and Rosenberg 1995).

At the watershed level, significant relationships were observed between chl *a* concentrations and agricultural land use (Table 5; Fig. 10), total nitrogen concentrations and agricultural land use (Fig. 11) as well as nonpoint nutrient loads (Table 5), whereas total phosphorus concentrations were unrelated to any watershed level variable (Table 5). These results relating eutrophication variables to watershed variables are consistent with results from both coastal plain (Jordan et al. 1997a,c) and piedmont watersheds (Jordan et al. 1997b) of the Chesapeake Bay. These studies also found that nitrogen concentrations were strongly and positively correlated with increasing proportion of croplands and that there was no correlation between phosphorus concentrations and land use. Total phosphorus concentrations were correlated with concentrations of suspended particulates (Jordan et al. 1997a,b,c), a variable not included in our study. The relationship of water column nitrogen levels to nonpoint source loads is consistent with the conclusions of Correll (1987) that nonpoint source discharges account for 65% of the nitrogen, 22% of the phosphorus and all of the silicate inputs into the Chesapeake Bay watershed. Nonpoint sources of nutrients are considered the leading cause of the remaining water quality problems in the United States (Novotny and Chesters 1989; Fulton et al. 1993). Controlling nonpoint nitrogen sources is essential to restoring and maintaining estuarine water quality (Valiela et al. 1997).

Benthic Community Condition and Watershed Variables

Although it seems intuitively obvious that human activities may affect the ecological condition of adjacent waters, demonstrating direct relationships between estuarine condition indicators and watershed level variables has been difficult (Comeleo et al. 1996). At the watershed level the positive relationship of the B-IBI with forested land use (Table 4; Fig. 5) indicates that combined high levels of agricultural and urban land use result in altered benthic community structure relative to reference conditions. Potential causes of the altered benthic community condition include sediment contamination effects, low dissolved oxygen events and enrichment effects associated with intermediate levels of eutrophication in the absence of low dissolved oxygen events. At intermediate levels of eutrophication, macrobenthic communities may be altered through increased abundances and/or biomass compared to reference conditions (Pearson and Rosenberg 1978; Dauer and Conner 1980; Ferraro et al. 1991). The B-IBI approach of Weisberg et al. (1997) assigns low categorical scores to both exceptionally low and exceptionally high values for abundance and biomass. The positive relationship of the B-IBI with forested land use in our study is consistent with results from freshwater ecosystems where macroinvertebrate community condition in streams is positively related to forested land use (Richards and Host 1994; Richards et al. 1996; Correll and Weller 1997). It is unlikely that forested land cover in Chesapeake Bay watersheds will be greatly increased at the expense of urban and agricultural land use. Increasing the spatial extent of riparian vegetated buffer zones may, to some extent, ameliorate the effects of reduced forested land area (Correll 1997; Correll and Weller 1997; Valiela et al. 1997).

Benthic community condition was significantly correlated with population density and nitrogen loading below the fall line but not above the fall line, suggesting that near-field factors (below the fall line) have a greater effect than far-field factors. These results in our study were primarily due to the patterns in the highly urbanized Patapsco River (Fig. 6) and the highly agricultural Nanticoke River (Fig. 7). The negative relationship of benthic community condition with nitrogen loadings below the fall line and absence of a relationship with phosphorus loadings is consistent with the conclusion that nitrogen concentrations are more important to eutrophication in estuarine and coastal ecosystems (Ryther and Dunstan 1971; Boynton et al. 1982; D'Elia et al. 1986; Howarth 1988; Malone et al. 1988, 1996; Jordan et al. 1991; Correll et al. 1992; Oviatt et al. 1995; Seitzinger and Sanders 1997; Valiela et al. 1997). Benthic community condition was not related to nonpoint nutrient loads. However, water column concentrations of total nitrogen were correlated with nonpoint loads and not with point source loads. The correlation of benthic response with point source loadings of nutrients is probably related to sediment contaminant effects as indicated by the correlation between sediment contaminant levels and point source loads of both nitrogen and phosphorus (Table 4; Fig. 9). Degraded benthic communities associated with low dissolved oxygen levels were spatially extensive while degraded benthic communities associated with sediment contaminants were spatially limited to highly urbanized regions.

Limitations of this Study

One limitation of our analyses is that associations between benthic responses and exposure measures were evaluated on the basis of average values for Bay segments, rather than by individual site values. This was done because each of the

Chesapeake Bay monitoring program elements is conducted independently, and the temporal and spatial distribution of sampling differs considerably among them. Using stratum averages reduces the statistical power available to identify associations in several ways. First, it limits the data in the analysis to the number of segments rather than the number of samples collected. Second, important small-scale spatial information is lost by averaging values over large areas, such as the CBP segments. Pollution effects on sedimentary communities are often patchy, and areas with high concentrations of contaminants and poor biotic condition may occur within 100 meters of places with low contaminant concentrations and acceptable biotic condition. In our analysis, contaminant exposure and benthic condition in spatially heterogeneous segments were averaged, potentially obscuring higher degrees of association observable at smaller spatial scales.

As Table 1 indicates, the numbers of observations of exposure variables were large, except for sediment contaminants. Of the 46 strata (not partitioned by depth), no contaminant data were available for 13 segments; for another 12, chemical concentrations were characterized by fewer than three samples. The segments for which little or no data were available were mostly smaller Bay segments (e.g., most of the segments, labeled either ET or WT on Fig. 1); therefore, our conclusions about the relative importance of contaminants to biotic response are probably valid Bay-wide. However, contaminants were found to be important mostly in embayments. The absence of data for some of these smaller systems leaves open the possibility that contaminant problems also exist there.

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