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Long-Term Trends in the Macrobenthos and Water Quality of the Lower Chesapeake Bay (1985–1991)

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Long-term trends in macrobenthic communities of the lower Chesapeake Bay, USA, were examined using data collected quarterly (March, June, September and December) from 1985 to 1991 at 16 stations along a salinity gradient from tidal freshwater regions of the major tributaries (James, York and Rappahannock rivers) to the polyhaline region of the main-stem of Chesapeake Bay. A non-parametric trend analysis procedure was applied to five parameters characterizing macrobenthic community structure: community biomass, species richness, abundance of individuals, proportion of biomass composed of opportunistic species (opportunistic biomass composition) and proportion of biomass composed of equilibrium species (equilibrium biomass composition). For the parameters tested 36 trends were detected. For community biomass, five trends were significant; all had positive slopes and occurred in the James and York rivers. For species richness, six trends were significant; all had positive slopes with three trends in the James River, two trends in the York River and one trend in the main-stem of Chesapeake Bay. For abundance of individuals, 17 trends were detected; all abundance trends were seasonally dependent, had positive slopes and occurred at 12 of the 16 stations. For opportunistic biomass composition, four trends were significant; all had positive slopes with one trend in the lower Rappahannock River and three trends in the main-stem of Chesapeake Bay. For equilibrium biomass composition four trends were significant; two trends had positive slopes (one in the James River and one in the York River) and two trends had negative slopes (one in the Rappahannock River and one in the main-stem of Chesapeake Bay). Trends in the James and York rivers were considered to indicate improving conditions for the benthos, while trends in the lower Rappahannock River and the main-stem of the Chesapeake Bay were considered to indicate deteriorating conditions. Deteriorating conditions for the benthos were associated with regions exposed to summer, low dissolved oxygen events. The trends in the indicators of benthic biological community health were inferentially related to trends observed in water quality conditions in the tributaries and main-stem of Chesapeake Bay. All major water quality and biotic trends appeared to correspond in an ecologically meaningful manner.

The Chesapeake Bay is the largest estuary in the United States and historically has supported some of the world's most productive commercial fisheries (USEPA, 1983). Environmental conditions in the Chesapeake Bay and its tributaries have deteriorated significantly over the past 50 years as indicated by declines in a variety of living resources, including submerged aquatic vegetation, finfish and shellfish. Declines in living resources have been attributed primarily to increases in eutrophication and toxic substances. Eutrophication, largely the result of nutrient enrichment from agricultural run-off and other non-point sources, has resulted in algal blooms and low dissolved oxygen conditions (Smith *et al.*, 1992). Algal blooms may affect recruitment, growth and survival of the benthos through *1.* changes in the quality and quantity of food sources for larval, juvenile and adult benthos (Christensen & Kanneworff, 1985; Marsh & Tenore, 1990; Kemp & Boyton, 1992); and *2.* by producing extended periods of low dissolved oxygen. The occurrence of low dissolved oxygen events in the Chesapeake Bay is well documented (Taft *et al.*, 1980; Officer *et al.*, 1984; Kuo & Neilson, 1987; Smith *et al.*, 1992). These events occur most commonly in deeper channels (generally, depths below the pycnocline), but wind-driven seiching can bring oxygen-depleted bottom waters over adjacent shallow areas (Tuttle *et al.*, 1987; Breitburg, 1990). The benthic community shows the first and most severe effects because low dissolved oxygen events typically begin near the bottom. Low dissolved oxygen effects on benthic communities of the Chesapeake Bay have previously been reported by Holland *et al.* (1977, 1987), Pihl *et al.* (1991), Dauer *et al.* (1992) and Dauer (1993a). Toxic substances, primarily from industrial and municipal point sources, become particle bound and eventually concentrated in fine-grained sediments (Swartz & Lee, 1980). Low dissolved oxygen events and high concentrations of toxic materials in sediments in the Chesapeake Bay result in reduced levels of benthic community parameters (Dauer, 1993a; Dauer *et al.*, 1993).

The marked decline in the water quality and resources of the Chesapeake Bay over the past several decades stimulated the establishment of directives to better manage the bay and its associated river systems. State and federal agencies developed a co-operative agreement to address the condition of the bay. The Chesapeake Bay Agreements of 1983 and 1987 were implemented between the US Environmental Protection Agency (EPA), the State of Maryland, the Commonwealths of Pennsylvania and Virginia and the District of Columbia to share the responsibilities for a comprehensive, long-term programme to 'revitalize' the bay. The monitoring of environmental conditions is considered vital to assessing the progress of the Best Management Practices being implemented throughout the bay and its tributaries. A major focus in the monitoring programme is to detect natural and/or man-induced changes in environmental conditions over time. The Chesapeake Bay Monitoring Program initiated the generation of a database, which will enable the federal and state authorities to discern long-term trends in the environmental conditions in the bay.

Long-term monitoring of macrobenthic communities of the lower Chesapeake Bay has been conducted quarterly (March, June, September, December) since March 1985 at 16 stations stratified by salinity–sedimentary regions. Parameters associated with macrobenthic community structure, water quality and sediment particle distribution are measured along the estuarine gradient from tidal freshwater to polyhaline regions within the major tributaries (James, York and Rappahannock rivers), the southern branch of the Elizabeth River and the main-stem of the lower Chesapeake Bay. Data reported in this study were collected as part of the ongoing Benthic Biological Monitoring Program of the Chesapeake Bay Program for the Virginia portion of the Chesapeake Bay. The primary purposes of the benthic monitoring program are *1.* to characterize the present health of regional areas of the lower Chesapeake Bay as indicated by the structure of the benthic communities (Dauer, 1993a) and *2.* to conduct trend analyses on long-term data to relate spatial and temporal trends of the benthic communities to changes in water and sediment quality within the lower Chesapeake Bay (Dauer, 1991).

In this study a non-parametric trend analysis procedure was applied to the benthic data set for a 7-year period from March 1985 to December 1991. Five parameters characterizing macrobenthic community structure were tested for trends: community biomass, species richness, abundance of individuals, proportion of biomass composed of opportunistic species (opportunistic biomass composition) and proportion of biomass composed of equilibrium species (equilibrium biomass composition). The selection of these parameters was based upon the assumption that healthy benthic communities can be characterized by *1.* high biomass dominated by relatively long-lived and often deep-dwelling species and *2.* high species richness (Dauer, 1993a). Based upon this assumption positive slopes in all parameters, except opportunistic biomass composition, would indicate improving conditions. A negative slope for opportunistic biomass would indicate improving conditions. Interpretation of trends for abundance of individuals is particularly problematic and no *a priori* expectations were developed.

Methods

Station locations

Sixteen stations in the lower Chesapeake Bay have been sampled since March 1985 as part of the Benthic Biological Monitoring Program of the Chesapeake Bay Program. Stations are located within the main-stem of the bay and the major tributaries—the James, York and Rappahannock rivers (Fig. 1). In the tributaries, stations were located within the tidal freshwater zone (TF5.5, TF4.2, TF3.3), turbidity maximum (transitional) zone (RET5.2, RET4.3, RET3.1), lower estuarine mesohaline muds (LE5.2, LE4.1, LE3.2) and lower estuarine polyhaline silty sands (LE5.4, LE4.3). The tidal freshwater station within the York River estuary was located in the Pamunkey River. In the main-stem of the bay three stations were located off the mouths of the major tributaries (CB8.1, CB6.4, CB6.1) and two stations in the deeper channels near the bay mouth (CB7.3E) and above the Rappahannock River near the Virginia–Maryland border (CB5.4).

Data collection

On each collection date three replicate box core samples were collected for benthic community analysis. Each replicate had a surface area of 184 cm^2, a minimum depth of penetration to 25 cm, was sieved on a 0.5 mm screen, relaxed in dilute isopropyl alcohol and preserved with a buffered formalin–rose bengal solution. In the laboratory each replicate was sorted and all the individuals identified to the lowest possible taxon and enumerated. Biomass was estimated for each taxon as ash-free dry weight (AFDW) by drying to constant weight at 60°C and ashing at 550°C for 4 h. Biomass was expressed as the difference between the dry and ashed weight.

At each station on each collection date: *1.* a 50-g sub-sample of the surface sediment was taken for sediment analysis; *2.* bottom salinity, temperature and dissolved oxygen were measured; and *3.* water depth was recorded. See Dauer (1993a) for a summary of salinity and sedimentary characteristics of each station and Dauer *et al.* (1992, 1993) for a summary of the pattern of bottom oxygen values.

Benthic community parameters

Trend analysis was performed on the five benthic community parameters identified earlier. All parameters were calculated on a per replicate basis. Community biomass included ash-free dry weights for all species. Species richness was calculated as the mean number of species per replicate. This estimate of species richness within a standard area of bottom is highly correlated with informational indices that are often used in benthic

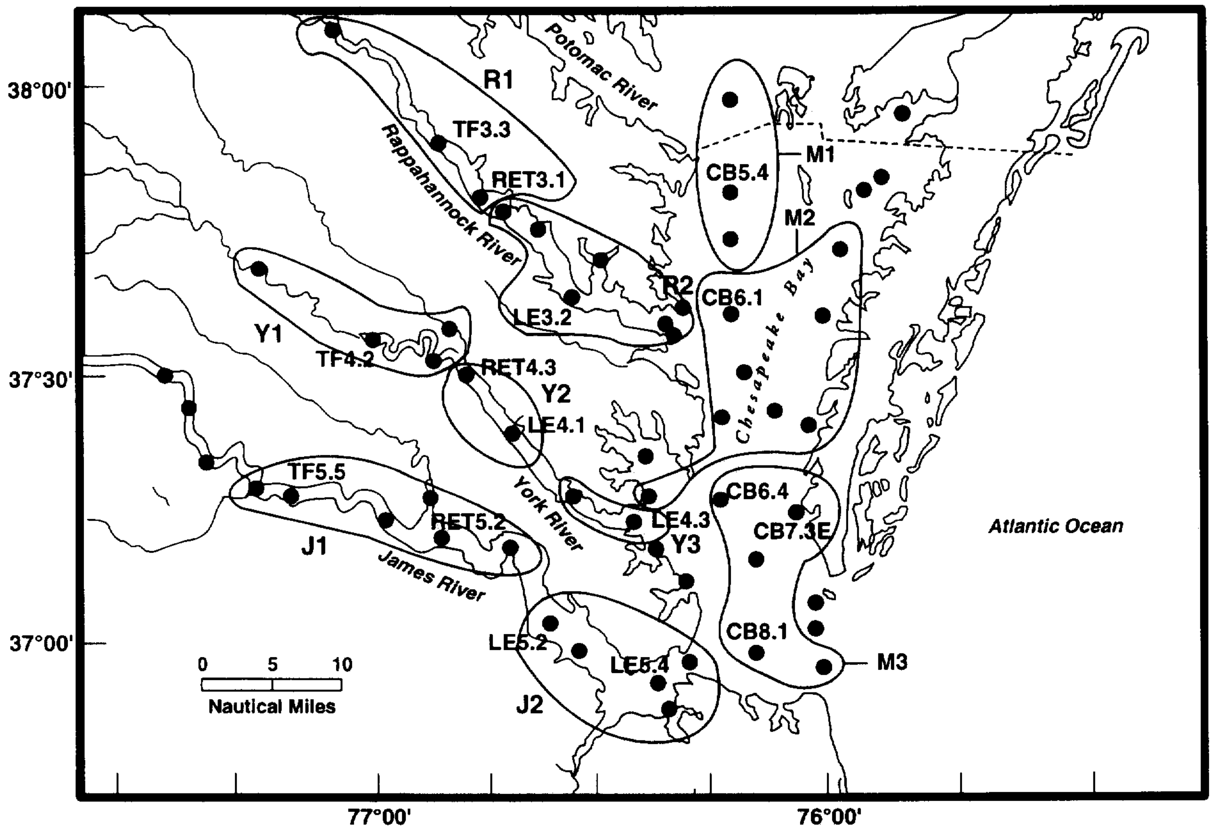

Fig. 1 Map of study area, indicating benthic sampling stations and water quality monitoring segments. The segments represent a subset of regions monitored for the Chesapeake Bay Water Quality Monitoring Program: only those segments containing benthic biological monitoring stations have been included and the segments have been renumbered for simplicity of presentation.

monitoring programmes (Dauer *et al.*., 1989), but is more directly interpretable. Abundance of individuals was the mean number of individuals per replicate. The percentage of community biomass accounted for by two indicator species groups was also used to characterize the benthic communities. The two indicator species groups were: *1.* an opportunistic species group and *2.* an equilibrium species group. The opportunistic species group consisted of relatively short-lived, eurytopic species often characterized as dominating disturbed or stressed habitats, while the equilibrium species group consisted of relatively long-lived species that dominate the community biomass in undisturbed or unstressed habitats. See Dauer (1991, 1993a) and Dauer *et al.* (1992) for a list of the species included in the two groups. For this study the opportunistic species group was expanded to include all insect larvae. More than 400 taxa of macrobenthic invertebrates were identified during this study; however, only 26 taxa were classified as opportunistic or equilibrium. Therefore, trends in opportunistic and equilibrium composition were not necessarily inversely related.

Water quality parameters

Water quality parameters are monitored throughout the Chesapeake Bay main-stem and tributaries approximately two times per month from March to October and once per month from November to February at 56 stations. Trend analyses are conducted on the water quality data sets periodically (Alden *et al.*, 1991, 1992, 1993) to track major long-term changes in environmental conditions throughout the bay. In interpreting the long-term trends for the benthos, corresponding trends in water quality were considered for the following selected parameters: surface and bottom total nitrogen; surface and bottom total phosphorus; surface chlorophyll-*a*; bottom dissolved oxygen; and bottom salinity. Detailed discussions of these and other water quality trends in the Chesapeake Bay are presented elsewhere (Alden *et al.*, 1991, 1992, 1993).

Trend analysis

Long-term trends were analysed by a series of powerful non-parametric trend tests. Overall trends in the data were analysed by the seasonal intra-block sign test based on the Kendall Tau statistic described by Hirsch *et al.* (1982) and the aligned rank test described by Sen (1968). Trends unique to certain seasons, to certain stations or to the interaction of stations and seasons were analysed by a χ^2 protocol described by Van Belle & Hughes (1984). The median slopes of significant trends were determined by the Seasonal Kendall slope estimator (Gilbert, 1987). A recent study on representative data sets from the Chesapeake Bay Monitoring Program has indicated that these tests are generally quite powerful and robust, even when data violate most of the assumptions of parametric statistics (Alden *et al.*, 1990). Trends were considered significant if $p \leq 0.01$. Preliminary robustness analyses of the first 5 years of data indicated that even the least conservative trend tests of benthic parameters produced a Type I (α) error of slightly less than 5% when tested at $\alpha = 0.01$. The trend tests for most of the benthic data were found to be quite robust, producing actual Type I errors that were less than or equal to the selected α level.

Results

Table 1 summarizes the distribution of the 36 significant trends in macrobenthic community parameters detected in this study. All parameters were homogeneous over collection times except for abundance of individuals; therefore, for abundance of individuals all trends were examined for each of the four collection times (March = spring, June = summer, September = autumn, December = winter). There were 17 significant trends for abundance of individuals; all trends had positive slopes and the trends were widespread in occurrence in each tributary and the main-stem of Chesapeake Bay, occurring at 12 of the 16 stations.

In the James River, 12 long-term trends were significant and all trends had positive slopes. In the York River, 10 long-term trends were significant and all trends had positive slopes. In the Rappahannock River five temporal trends were significant. In contrast to the James and York rivers, no trends in biomass or species richness occurred in the Rappahannock River; however, there was a single trend in opportunistic biomass composition with a positive slope and a single trend in equilibrium biomass composition with a negative slope.

In the main-stem of Chesapeake Bay, nine trends were significant. Opportunistic biomass composition had a positive slope at three stations and equilibrium biomass composition had a negative slope at one station. There was a single positive slope in species richness.

Figure 2 is presented as representative of trends at a station (LE4.3) consistent with the expectation of improving conditions for the benthos—increasing community biomass (Fig. 2(A)), increasing species richness (Fig. 2(B)), increasing equilibrium biomass composition (Fig. 2(C)) and seasonally increasing abundance of individuals (Fig. 2(D)). The increase in community biomass and equilibrium biomass composition corresponded to increases in the bivalves *Mercenaria mercenaria* (no individuals collected until 1990;

TABLE 1
Trend analysis summary (1985–1991).

Stations	Community biomass	Species diversity	Opportunistic biomass	Equilibrium biomass	Abundance (individuals)
James River					
TF5.5	+0.144	+1.00			+744 (Su)
RET5.2	+0.114	+0.33			+687 (Sp) +229 (W)
LE5.2	+1.373			+3.1	
LE5.4		+1.29			+1040 (Sp) +1183 (W)
York River					
TF4.2	+0.057	+0.25			+114 (F)
RET4.3					+916 (W)
LE4.1					+820 (W)
LE4.3	+2.461	+2.71		+4.7	+1288 (Su) +1641 (W)
Rappahannock River					
TF3.3				−0.2	+1145 (Su) +458 (F)
RET3.1					+343 (F)
LE3.2			+5.6		
Main-stem of Bay					
CB5.4			+5.4		664 (Sp)
CB6.1			+1.4		
CB6.4			+2.5	−7.1	
CB7.3E					+1689 (Sp) +1087 (W)
CB8.1		1.00			+744 (Su)

+, −: Indicates, respectively, a significant positive or negative slope for the parameter indicated ($p \leq 0.01$). Abundance had significant station–season interaction. Letter in parentheses indicates the season for which a significant trend was found (Sp = March, Su = June, F = September, W = December). Slopes for community biomass are in g m^{-2}, for species diversity in species per replicate, for opportunistic and equilibrium biomass in %, and for abundance in individuals m^{-2}.

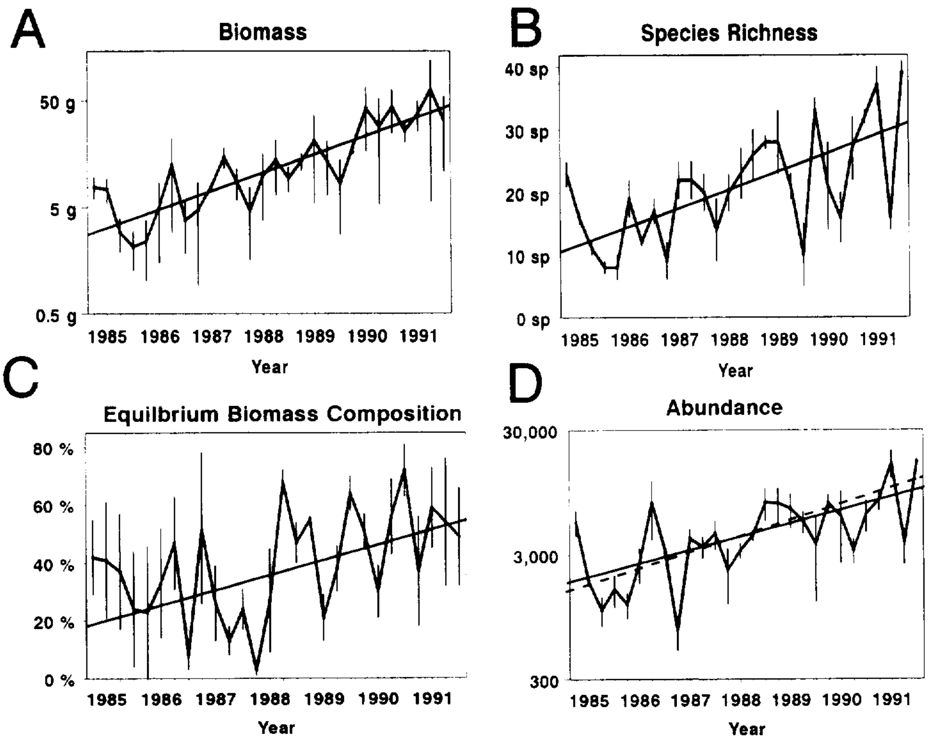

Fig. 2 Trends at stations LE4.3 representative of improving conditions for the benthos. A: Biomass in g m^{-2}. B: Species richness in species per replicate. C: Percentage of community biomass composed of equilibrium species. D: Abundance in individuals m^{-2} (solid line is the trend for June data and dashed line is the trend for December data).

AFDW biomass for 1985–1989 = 0.0 g m^{-2}, for 1990–1991 = 7.6 g m^{-2}), *Mya arenaria* (no individuals collected until 1988; AFDW biomass for 1985–1989 = 0.4 g m^{-2}, for 1990–1991 = 4.3 g m^{-2}), *Anadara ovalis* (no individuals collected until 1986; AFDW biomass for 1985–1989 = 0.8 g m^{-2}, for 1990–1991 = 5.5 g m^{-2}), *Anadara transversa* (AFDW biomass for 1985–1989 = 0.7 g m^{-2}, for 1990–1991 = 2.7 g m^{-2}) and the polychaete *Clymenella torquata* (AFDW biomass for 1985–1989 = 2.1 g m^{-2}, for 1990–1991 = 4.1 g m^{-2}). All of these species have been previously classified as equilibrium species (Dauer, 1991, 1993a; Dauer *et al.*, 1992).

Figure 3 is presented as representative of trends at four stations consistent with at least one of the expectations of deteriorating conditions for the benthos—increasing composition of opportunistic species. The increase in composition of opportunistic species corresponded with increases in the bivalve *Mulinia lateralis* at all four stations (at LE3.2, AFDW biomass for 1985–1989 = 0.039 g m^{-2}, for 1990–1991 = 0.599 g m^{-2}; at CB5.4, AFDW biomass for 1985–1989 = 0.022 g m^{-2}, for 1990–1991 = 2.250 g m^{-2}; at CB6.1, AFDW biomass for 1985–1989 = 0.003 g m^{-2}, for 1990–1991 = 2.898 g m^{-2}; at CB6.4, AFDW biomass for 1985–1989 = 0.016 g m^{-2}, for 1990–1991 = 0.327 g m^{-2}), in the polychaete *Paraprionospio pinnata* at three of the four stations (at LE3.2, AFDW biomass for 1985–1989 = 0.139 g m^{-2}, for 1990–1991 = 0.522 g m^{-2}; at CB6.1, AFDW biomass for 1985–1989 = 0.518 g m^{-2}, for 1990–1991 = 1.547 g m^{-2}; at CB6.4, AFDW biomass for 1985–1989 = 0.401 g m^{-2}, for 1990–1991 = 2.731 g m^{-2}), the polychaete *Nereis succinea* at LE3.2 only (AFDW biomass for 1985–1989 = 0.139 g m^{-2}, for 1990–1991 = 0.836 g m^{-2}), the polychaete *Leitoscoloplos fragilis* at CB5.4 only (AFDW biomass for 1985–1989 = 0.033 g m^{-2}, for 1990–1991 = 0.313 g m^{-2}) and the polychaete *Mediomastus ambiseta* at CB5.4 only (AFDW biomass for 1985–1989 = 0.033 g m^{-2}, for 1990–1991 = 0.146 g m^{-2}).

Table 2 presents the trends detected in selected water quality parameters for the full monitoring period. However, data from the last 2.5 years of monitoring in certain of the regions of the bay exhibited dramatic changes in the magnitude and/or direction of water quality trends in comparison to that reported for the first 5 years of monitoring (Alden *et al.*, 1991, 1992). Figure 4 presents representative examples of how trends have appeared, disappeared or even reversed themselves due to changes in water quality conditions during this period of time. Therefore, Table 2 contains symbols to footnote major changes in the direction/magnitude of trends that were observed between the 5-year period from 1985–1989 and the 7-year period from 1985–1991. Trends were considered to be approximately equal if trend slopes did not differ by more than 10% between the 5- and 7-year analyses, or if no trends were detected during either period. If the magnitude of the change in trends produced by the two sets of analyses was greater than 10% of the 5-year annual trend rate, the direction of the change is indicated in Table 2 with an arrow.

In general, increasing trends in nutrients (particularly nitrogen) that were observed in the tributaries during the

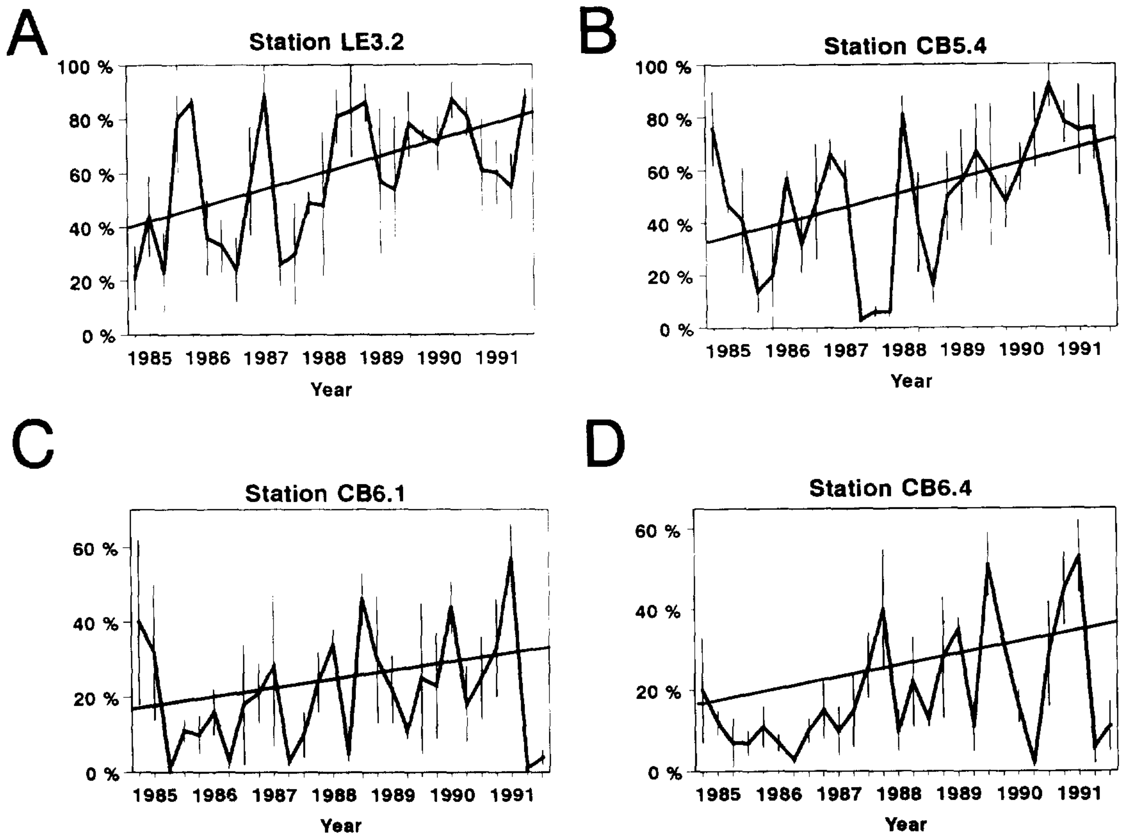

Fig. 3 Trends at stations representative of deteriorating conditions for the benthos. The percentage of community biomass composed of opportunistic species is shown. A: Station LE3.2. B: Station CB5.4. C: Station CB6.1. D: Station CB6.4.

first 5 years of monitoring (Alden *et al.*, 1991, 1992) have diminished or have reversed themselves in many of the regions of the James and York rivers. Trends in chlorophyll concentrations, which were observed to be increasing through the first 5 years (1985–1989), disappeared or were reversed in these regions over the entire 7-year period (1985–1991). Bottom dissolved oxygen of the James and York rivers did not display significant trends for either the 5- or 7-year period. On the other hand, data from the lower reach (R2) of the Rappahannock River displayed declining water quality conditions over the 7-year period that were more marked than those observed for the first 5 years: total nitrogen and total phosphorus displayed increasing trends; chlorophyll concentrations increased during spring and summer months; and bottom dissolved oxygen exhibited an overall decreasing trend (Table 2). Bottom salinities in the lower reaches of all three tributaries displayed a decreasing trend, a pattern that was particularly evident during the last 2.5 years of the monitoring.

In the main-stem of the bay, the water quality trends in the M1 region did not change much between the 5-year period (1985–1989) and the full 7-year period (1985–1991), with the only significant trend for either period being a decrease in bottom total phosphorus (Table 2). However, in the other two regions (M2 and M3), nitrogen tended to increase, autumn chlorophyll concentrations increased, and bottom dissolved oxygen concentrations decreased (particularly in M3).

Discussion

Interpretation of the ecological significance of the trends observed in this study is dependent upon the expected relationship between benthic community structure and levels of eutrophication and/or sediment contamination. Highly stressed marine and estuarine macrobenthic communities are characterized by: *1.* low levels of species diversity (or species richness), abundance (number of individuals) and biomass; *2.* dominance by species that are short-lived (opportunistic, pioneering, *r*-selected, stress tolerant), shallow-dwelling and primarily annelids; and *3.* the absence or rarity of species that are long-lived (equilibrium, *k*-selected), often deep-dwelling within the sediment and representative of a diversity of major taxa (Boesch, 1977; McCall, 1977; Pearson & Rosenberg, 1978; Rhoads *et al.*, 1978; Gray, 1979; Rhoads & Boyer, 1982; Warwick, 1986; Dauer, 1993a). However, the relationship between benthic community structure and intermediate levels of stress from eutrophication and/or contamination of sediments is often difficult to detect or interpret for eutrophication (Gray, 1992), or is not well understood for sediment contamination (Scott, 1989).

The most widely accepted relationship between benthic community structure and level of eutrophication (or organic enrichment) is the SAB model of Pearson & Rosenberg (1978) that summarizes the relationship between patterns of species richness (S), abundance of individuals (A) and biomass (B) to organic enrichment,

TABLE 2
Trend analysis summary (1985–1991) for water quality.

Segment (benthic stations)	STN	BTN	STP	BTP	SChla	BDO	BSAL
James River							
J1	−0.034			+0.010	−0.210		
(TF5.5; RET5.2)	↓	↓	≈	≈	(Su)↓	≈	≈
J2	+0.042	+0.020	+0.006	+0.007	+0.571		−0.67
(LE5.2, LE5.4)	(Su)		(Sp)	(Sp)	(Sp)		
			+0.003	+0.010	−0.444		
	≈	≈	(Su)↓	(Su)↓	(Su)↓	≈	↓
York River							
Y1			+0.005	+0.008			
(TF4.2)				(Sp)			
				+0.019			
	↓	↓	≈	(Su)≈	↓	≈	≈
Y2	+0.030	+0.033	+0.007	+0.010	+0.798		−0.840
(RET4.3; LE4.1)	↓	↓	↓	↓	↓	≈	↓
Y3	↓	↓	+0.003	+0.003			−0.563
(LE4.3)			≈	≈	↓	≈	↓
Rappahannock River							
R1	+0.024	+0.040	+0.008	+0.010			−0.568
(TF3.3; RET3.1)	↓	↓	↓	↓	↓	≈	↓
R2	+0.025	+0.061	+0.003	+0.005	+3.14	−0.200	−0.700
(LE3.2)	(Sp)	(Su)	(W)		(Sp)		
	+0.058		+0.004		−0.542		
	(Su)↑	↑	(Su)↑	↑	(Su)↑	↓	↓
Main-stem of Bay							
M1				−0.003			
(CB5.4)	≈	≈	≈	≈	≈	≈	≈
M2	+0.008	+0.016		−0.001	+0.910	−0.281	−0.379
(CB6.1)	↑	↑	≈	≈	(F)↑	(W)↓	(Sp)≈
M3	+0.030		−0.003	−0.004	+0.819	−0.130	−0.540
(CB6.4; CB7.3E; CB8.1)	(Sp)				(F)↑		(Sp)
	+0.017				−1.790		
	(Su)↑	≈	≈	≈	(Sp)↓	↓	≈

S = Surface, B = bottom, TN = total nitrogen, TP = total phosphorus, Chla = chlorophyll *a*, DO = dissolved oxygen and SAL = salinity. +, −: Indicates a significant ($p \leq 0.01$) positive or negative slope, respectively. Codes in parentheses represent season-specific trends: W = winter, Sp = spring, Su = summer and F = fall. Symbols represent qualitative comparisons of 7-year trends to 5-year trends: ↓ = Decrease in trend rate compared to that from 5-year analysis; ↑ = increase in trend rate compared to that from 5-year analysis; ≈ = approximately equal trend rate compared to that from 5-year analysis. Segments, stations and abbreviations are as in Table 1.

primarily from point sources such as effluents from sewage treatment plants and pulp mills. The SAB model depicts benthic community patterns at increasing distances from the effluent or increasing time since the removal of the effluent. Benthic community parameters of the SAB model increase from low levels nearest the source of organic enrichment to higher levels at a distance, in space or time, from the source of organic enrichment. However, moderate levels of organic enrichment may result in species richness, abundance of individuals and biomass that are higher than values for benthic communities exposed to either high or low levels of organic enrichment (Pearson & Rosenberg, 1978; Dauer & Conner, 1980; Ferraro *et al.*, 1991; Fallesen, 1992). Therefore, trends in species richness, abundance of individuals and biomass must be cautiously interpreted.

The ABC method of Warwick (1986) is applicable to any source of ecological stress (Warwick *et al.*, 1987) and is based upon the relative dominance relationships of abundance of individuals and biomass (*k*-dominance curves). The ABC method is based upon the assumption that infrequently disturbed benthic communities are dominated in biomass by equilibrium species composed of individuals that are large in body size, relatively rare and long-lived, while frequently disturbed benthic communities are dominated in both biomass and abundance by opportunistic species composed of individuals that are small in body size, numerically abundant and short-lived. The ABC method has been widely tested (Warwick & Ruswahyuni, 1987; Warwick, *et al.*, 1987, 1990; Gray *et al.*, 1988; Warwick, 1988; Ibanez & Dauvin, 1988; Austen *et al.*, 1989; Ritz *et al.*, 1989) and although some problems have been found (Beukema, 1988; Weston, 1990; Dauer *et al.*, 1993), the theoretical basis of the approach is widely accepted.

Both the SAB model and the ABC method assume that highly stressed benthic communities are dominated in biomass and abundance by opportunistic species, while unstressed benthic communities are dominated in biomass, but not abundance, by equilibrium species. Consistent with these approaches, we consider trends in opportunistic species and equilibrium species composition of the benthic community to be the best indicators

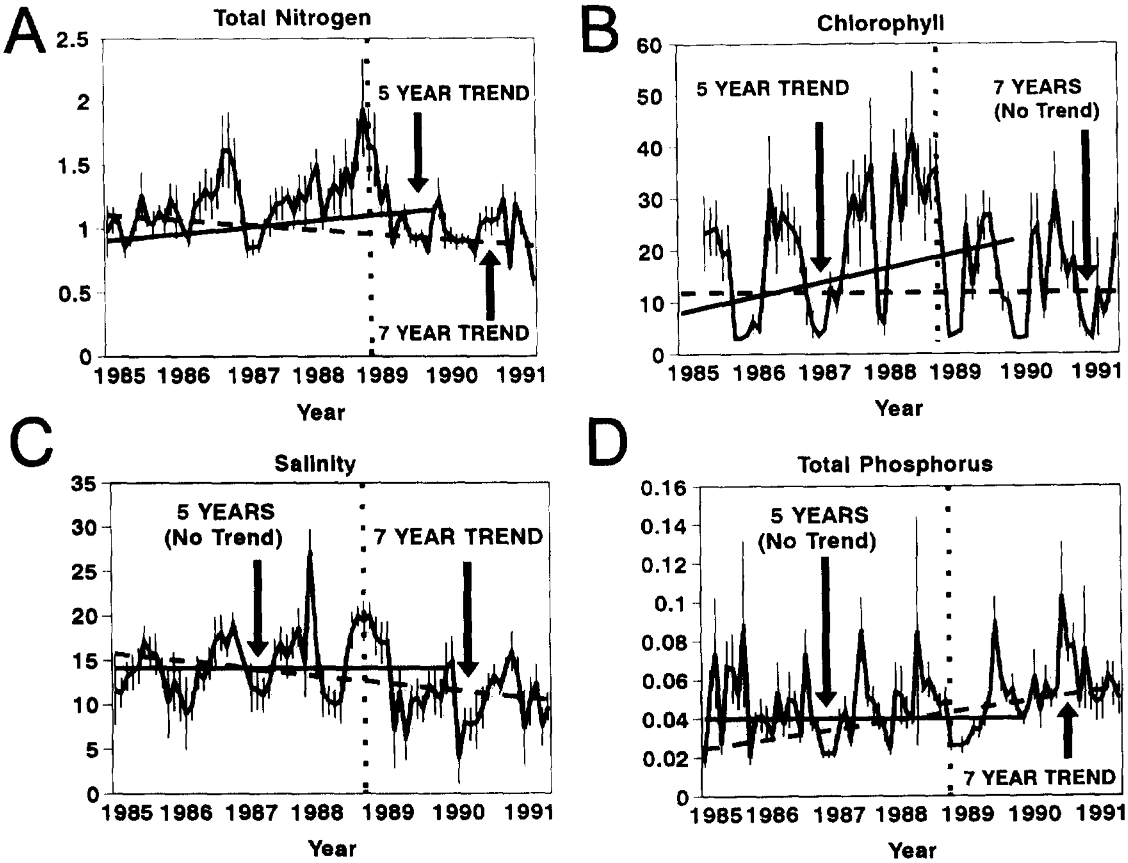

Fig. 4 Examples of changes in water quality trends observed between Year 5 and Year 7 of the monitoring programme: A: Trend reversal in surface total nitrogen concentrations for segment J1. B: Trend diminishment in chlorophyll concentrations for segment J1. C: Decreasing trend in bottom salinities for segment J2. D: Increasing trend in bottom total phosphorus concentrations for segment R2.

of the ecological significance of the trends observed in this study. Improving conditions for the benthos should be accompanied by a positive slope in equilibrium biomass composition and/or a negative slope for opportunistic biomass composition. Deteriorating conditions for the benthos should be accompanied by a negative slope in equilibrium biomass composition and/ or a positive slope for opportunistic biomass composition.

Based upon the expectations discussed earlier, the data in Table 1 indicate improving conditions for the benthos of the James and York rivers, and deteriorating conditions for the benthos of the Rappahannock River and the main-stem of Chesapeake Bay. The James and York rivers had all five trends of increasing community biomass, five of the six trends of increasing species richness and both trends of increasing equilibrium biomass composition. There were no trends in the James and York rivers indicative of deteriorating conditions. The Rappahannock River had a mixed pattern with all trends in abundance with positive slopes and equilibrium biomass composition declining at one station (TF3.3) and opportunistic biomass composition increasing at one station (LE3.2). The decline in equilibrium biomass composition at TF3.3 was due to declining biomass values for the bivalve *Rangia cuneata* (Dauer, 1993b). For the 5-year period of 1985–1989, *R. cuneata* averaged 63.1 g m^{-2} and for the 2-year period of 1990–1991 averaged 17.6 g m^{-2}. Conditions at this station, therefore, should be closely monitored. Station LE3.2 is subjected to low dissolved oxygen events during summer months (Dauer *et al.*, 1992) and the increase in opportunistic biomass composition indicates that conditions for the benthos at this station deteriorated in the period 1985–1991. The increase in opportunistic species composition at three stations and the decrease in equilibrium species composition at one station in the main-stem of Chesapeake Bay indicates that conditions for the benthos deteriorated, probably associated with low dissolved oxygen events that were previously reported for stations CB5.4 and CB6.1 (Dauer *et al.*, 1992).

Comparison with trends in the benthos for 1985–1989

Previously, Dauer (1991) reported trends in the macrobenthic communities of the Chesapeake Bay for the 5-year period from 1985–1989. A total of 25 trends were significant, including five trends with positive slopes for abundance of individuals that were not presented in Table 2 of Dauer (1991). In this study a total of 36 trends are reported for the 7-year period from 1985–1991. Compared to the 5-year period of 1985–1989, 11 trends continued, 14 trends were no longer significant and there were 25 new trends.

The conclusions of this study of improving conditions for the benthos of the James and York rivers, and deteriorating conditions for the benthos of the Rappahannock River and the main-stem of Chesapeake Bay, are consistent with the results of Dauer (1991). Dauer (1991) reported: *1.* six significant trends in community biomass with five positive slopes in the tributaries (in the James River at LE5.2; in the York River at TF4.2, RET4.3 and LE4.3; and in Rappahannock River at RET3.1) and one trend with a negative slope in the main-stem of Chesapeake Bay (CB8.1). *2.* Five seasonally dependent significant trends in species richness with four positive slopes in the tributaries (in the James River at LE5.2 for March data; in the York River at TF4.2 for December data; and at LE4.3 for June and September data) and one trend with a negative slope in the main-stem of Chesapeake Bay (at CB7.3E for June data). *3.* Six seasonally dependent trends in opportunistic biomass composition with four negative slopes in the tributaries (in the James River at LE5.2 for June data; in the York River at RET4.3 for June and September data; and at LE4.3 for December data) and two trends with positive slopes in the main-stem of Chesapeake Bay (at CB6.4 for December data and at CB6.1 for September data). *4.* Three significant trends in equilibrium biomass composition with one positive slope in the York River (RET4.3) and two negative slopes in the main-stem of Chesapeake Bay (CB7.3E, CB6.4).

Comparison with trends in water quality

The trends in water quality after 5 years of monitoring (1985–1989) suggested that conditions may have been declining in all three of the tributaries that were monitored (Alden *et al.*, 1991, 1992). However, these trends appeared to have reversed themselves in the James and York rivers during the last 2.5 years of the period from 1985–1991. Upward trends in nutrients tended to decrease or reverse themselves (Table 2; Fig. 4(A)). Likewise, increasing trends in chlorophyll concentrations tended to disappear (Table 2; Fig. 4(B)). It is difficult to determine whether the apparent improvement in water quality conditions was due to increased management efforts to control point and non-point sources of nutrients in these watersheds or due to climatological changes during the latter years of the study, which were reflected in decreased salinities (Table 2; Fig. 4(C)). Using regression models developed by the US Geological Survey (Smith *et al.*, 1982), Alden *et al.* (1992) reported that a dilution effect model was the 'best fit' for phosphorus in the James River, indicating that increased river flow would tend to decrease phosphorus concentrations. Regardless of the cause of the apparent improvement in water quality, a similar effect was not apparent for the lower reaches of the Rappahannock River, in which indicators of cultural eutrophication (i.e. increasing nutrients and chlorophyll, and decreasing bottom oxygen concentrations) tended to become more marked, particularly during the last 2.5 years of the study (Table 2; Fig. 4(D)).

The trends in the benthic biotic communities of the three tributaries appeared to reflect the patterns of water quality. The benthos in the James and York rivers tended to display trends indicative of increasing community health, while those in the Rappahannock River generally exhibited trends more indicative of stress. The last several years of the study period of 1985–1991, which displayed significant changes in water quality trends, were also observed to be particularly dynamic biologically. In comparing the findings of the current study to those of the 5-year period from 1985–1989 (Dauer, 1991), 19 of the 25 trends detected in the tributaries were new trends and an additional two trends were strengthened from seasonal to overall (year-round) significance. Each of these new or strengthened trends reinforced the speculation that ecological conditions were improving in the James and York rivers, but not in the lower Rappahannock River. Thus, the trends in the benthic biota appear to be at least inferentially related to the trends in the water quality of the tributaries.

The trend analyses of data from the main-stem of the bay suggested that water quality conditions for segments M2 and M3 had somewhat deteriorated (i.e. increasing nitrogen nutrients and seasonal chlorophyll concentrations, and decreasing bottom oxygen in M3; Table 2) over the monitoring period, particularly during the last several years. Decreasing salinities during the spring months (Table 2) suggest that increased run-off during this season may be responsible for these trends. Trends in the benthic biological communities appeared to be consistent ecologically with the observations of water quality trends; stations CB6.1 in M2 and CB6.4 in M3 displayed trends indicative of increased stress (i.e. increasing opportunistic biomass and decreasing equilibrium biomass). Water quality conditions at Stations CB7.3E and CB8.1 in segment M3 are moderated by coastal waters entering the mouth of the bay; therefore, water quality conditions at these stations would not be expected to be as stressful as those found at Station CB6.4. Water quality conditions did not change much for segment M1 during the course of the study, although there was a trend of increasing opportunistic biomass composition for the benthos, an indication of stress. This segment had the lowest mean bottom dissolved oxygen levels in the lower Chesapeake Bay (Table 2) and it represents the southern-most extension of the 'deep trench' of the bay that is seasonally stressed by hypoxic/anoxic conditions (Officer *et al.*, 1984; Alden *et al.*, 1991, 1992, 1993). The increase in opportunistic biomass composition, an indicator of stress, may be more related to other aspects of bottom water oxygen dynamics, such as the timing of the onset of hypoxia, rather than a long-term pattern in mean oxygen concentration. Thus, there also appears to be inferential agreement between the patterns in water quality conditions and the long-term trends in the benthic biological communities of the main-stem of the bay.

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