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Dynamics of an estuarine ecosystem: long-term trends in the macrobenthic communities of Chesapeake bay, (1985-1993)

Chesapeake Bay
Benthos
Trends
Estuary
Eutrophication

Baie de Chesapeake
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ABSTRACT

Long-term trends in subtidal macrobenthic communities of the lower Chesapeake Bay, USA, were examined using data collected quarterly (March, June, September and December) from 1985 through 1993 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 mainstem of Chesapeake Bay. In March 1989 two stations were added to the program in the mesohaline region of the Southern Branch of the Elizabeth River, a region characterized by contaminated sediments. 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). A total of 48 trends were detected. No trends were found at stations subjected to hypoxic/anoxic conditions or at stations with contaminated sediments. Trends in benthic community parameters affected by eutrophication may be difficult to interpret at moderate levels of organic enrichment or sediment contamination. Therefore, trends in functional groups (*e.g.* opportunistic and equilibrium species) of the benthic community may be the best indicators of the ecological significance of changes in community structure.

RÉSUMÉ

Dynamique d'un écosystème estuarien: tendances à long terme dans les communautés benthiques de la baie de Chesapeake.

Les tendances à long terme dans les communautés macrobenthiques subtidales ont été étudiées sur des données trimestrielles (mars, juin, septembre et décembre) collectées de 1985 à 1993 dans la partie basse de la baie de Chesapeake, U.S.A. Les seize stations de mesure se situent le long d'un gradient de salinité allant des eaux douces en provenance des principales rivières (James, York et Rappahannock) jusqu'aux eaux salées à l'entrée de la baie de Chesapeake. En mars 1989, deux stations supplémentaires ont été choisies dans la région mésohaline du bras sud de la rivière Elizabeth, caractérisé par des sédiments contaminés. Une méthode d'analyse des tendances non paramétriques a été appliquée à cinq caractéristiques du macrobenthos: biomasse, richesse des espèces, abondance des individus, proportion de la biomasse composée d'espèces opportunistes et proportion de la biomasse composée d'espèces d'équilibre. Au total, 48 tendances sont dénombrées. Aucune tendance n'est trouvée dans les stations soumises à des conditions hypoxiques/anoxiques ou dans les stations contaminées par les sédiments. En cas d'eutrophisation, les tendances dans les paramètres sont plus délicates à interpréter aux niveaux modérés d'enrichissement organique ou de contamination du sédiment. Par conséquent, les tendances des groupes fonctionnels (par exemple, espèces opportunistes et d'équilibre) de la communauté benthique sont les meilleurs indicateurs écologiques des changements dans la structure de la communauté

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INTRODUCTION

Environmental conditions in the Chesapeake Bay and its tributaries have deteriorated significantly over the past 50 years attributed primarily to increases in eutrophication and toxic substances (Dauer and Alden, 1995). Eutrophication can promote low dissolved oxygen events (Taft *et al.*, 1980; Officer *et al.*, 1984; Kuo and Neilson, 1987; Smith *et al.*, 1992) which affect recruitment, growth and survivorship of the benthos. 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 (1993). Toxic substances, primarily from industrial and municipal point sources, become particle-bound and eventually concentrated in fine-grained sediments (Swartz and 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, 1993; Dauer *et al.*, 1993). Studies of long-term trends in macrobenthic communities in the North Sea, Wadden Sea and the Skagerrak have indicated increased levels of benthic community abundance and biomass associated with moderate levels of eutrophication (Austen *et al.*, 1991; Beukema, 1989, 1991, 1992; Beukema and Cadée, 1986; Beukema and Essink, 1986; Rachor, 1990) consistent with the Pearson and Rosenberg model of eutrophication effects (Pearson and Rosenberg, 1978). The relationship between long-term trends in benthic communities and changing levels of organic input to the benthos is strong (Buchanan and Moore, 1986; Pearson *et al.*, 1986) although lags of up to two years may exist (Beukema, 1992).

Long-term monitoring of subtidal macrobenthic communities of the lower Chesapeake Bay has been conducted since March 1985. 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, 1993) 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, 1995; Dauer and Alden, 1995).

The purpose of this study is to present the long-term trends in the macrobenthic communities for the nine year period of 1985-1993 and to compare the present results with those of previous studies of the lower Chesapeake Bay (Dauer, 1991, 1995; Dauer and Alden, 1995).

METHODS

Station locations

Sixteen stations in the lower Chesapeake Bay have been sampled quarterly (March, June, September, December) since March 1985 as part of the Benthic Biological Monitoring Program of the Chesapeake Bay Program. Stations were located within the mainstem 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 mainstem 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). In March 1989 two stations were added in the Southern Branch of the Elizabeth River (SBE2, SBE5), a region characterized by contaminated sediments (Dauer *et al.*, 1993). Long-term average salinity, water depth and sedimentary parameters for each of the stations is presented in Table 1 of Dauer (1993).

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 within the sediment, 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 four hours. Biomass was expressed as the difference between the dry and ashed weight.

At each station on each collection date a 50 g subsample of the surface sediment was taken for sediment analysis; salinity, temperature and dissolved oxygen were measured at the bottom; and water depth was recorded. See Dauer *et al.* (1992) for a summary of the pattern of bottom oxygen values at each station and Dauer *et al.* (1993) for a summary of the distribution of contaminants in the sediments.

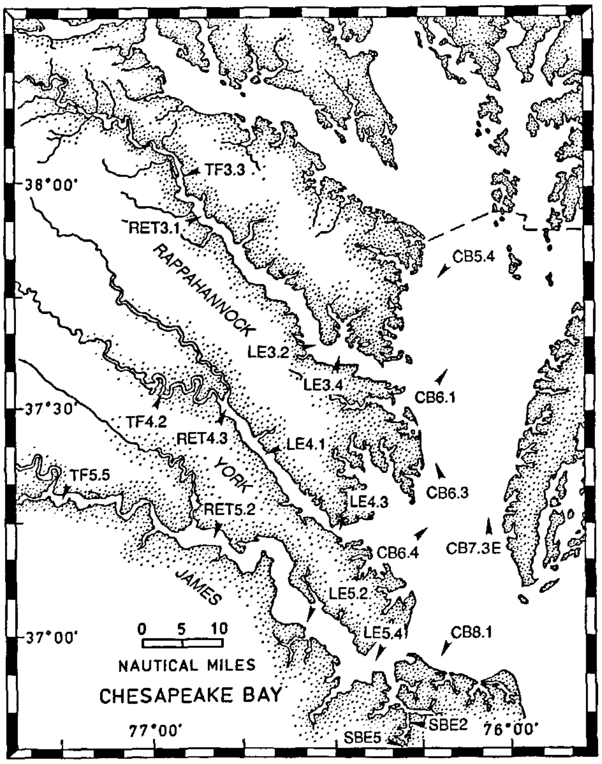

Figure 1

Map of lower Chesapeake Bay showing station locations in the mainstem of the bay (CB) and the James, York and Rappahannock rivers.

Trend analysis

In this study a non-parametric trend analysis procedure was applied to the benthic data set for a nine year period from March 1985 to December 1993. 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, 1993). 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. Trends in benthic community parameters affected by eutrophication may be difficult to interpret at moderate levels of organic enrichment or sediment contamination. Therefore, trends in functional groups (e.g. opportunistic and equilibrium species) of the benthic community may be the best indicators of the ecological significance of changes in community structure.

Long-term trends in the benthic data set were analyzed by a series of powerful non-parametric trend tests. Overall trends in the data were analyzed 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 analyzed by a chi-square protocol described by Van Belle and 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 $p<0.01$. Preliminary robustness analyses of the first five years of data indicated that even the least conservative trend tests of benthic parameters produced a Type I (alpha) 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 alpha level.

Benthic community parameters

Trend analysis was performed on the five benthic community parameters identified above. 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 (*e.g.* the Shannon Weiner Index) that are often used in benthic monitoring programs (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 functional species groups was also used to characterize the benthic communities. The two functional 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, 1993) 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 either opportunistic or equilibrium. Therefore, trends in opportunistic and equilibrium composition were not necessarily inversely related.

RESULTS

Table 1 summarizes the distribution of the 48 significant trends 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 by each of the four collection times (March, June, September, December). There were 27 significant trends for abundance of individuals; 26 trends had positive slopes and were widespread in occurrence in each tributary and the mainstem of Chesapeake Bay, one negative trend occurred in the York River at station RET4.3.

In the James River, 14 long-term trends were significant and all trends had positive slopes except for a single negative slope for opportunistic biomass at TF5.5. In the York River, 10 long-term trends were significant and all trends had positive slopes except for a single negative slope for opportunistic biomass at TF4.2 and a single negative slope for abundance of individuals in June samples at station RET4.3. In the Rappahannock River 7 long-term trends were significant and all trends had positive slopes. In the mainstem of Chesapeake Bay, 17 trends were significant and all trends had positive slopes except for equilibrium biomass composition at station CB6.4. Stations subjected to summer low dissolved oxygen events (LE3.2, CB5.4, see Dauer *et al.*, 1992, 1993; Dauer, 1993) or to contaminated sediments (SBE2, SBE5 see Dauer *et al.* 1992; Dauer, 1993) did not have any significant trends.

Figure 2 is presented as representative of trends at a station (LE4.3) consistent with the expectation of improving conditions for the benthos. At this station there were trends of increasing community biomass (Fig. 2*a*) and increasing species richness (Fig. 2*b*). In addition the abundance of individuals increased in three of the four collection seasons (March, June, December). The increase in community biomass corresponded with increases in the bivalves *Mercenaria mercenaria, Mya arenaria, Anadara ovalis, Anadara transversa*, and the polychaete *Clymenella torquata*. All of these species have been previously classified as equilibrium species (Dauer, 1991, 1993; Dauer *et al.* 1992). There were no significant trends in the community composition parameters of opportunistic or equilibrium groups at this station.

Figure 3 shows trends at a station (CB6.4) previously characterized (Dauer and Alden, 1995) as consistent

Table 1

Trend Analysis Summary (1985-1993). +, –: 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 (M, March, J, June, S, September, D, December). Slopes for Community Biomass are in g/m^{-2}, for Species Richness in species per replicate, for Opportunistic and Equilibrium Biomass in percent, and for Abundance in individuals per m^2. All slopes are annual slopes (yr^{-1}).

Stations	Community Biomass	Species Richness	Opportunistic Biomass	Equilibrium Biomass	Abundance (Individuals)
James Rivers					
TF5.5	+0.172	+1.00	−3.1		+1,382 (M)
					+876 (J)
					+437 (S)
					+702 (D)
RET5.2		+0.25			+515 (M)
LE5.2	+0.744			+1.4	+379 (M)
LE5.4					+2,003 (M)
					+607 (D)
York River					
TF4.2	+0.057	+0.33	−4.3		+229 (S)
RET4.3					−223 (J)
LE4.1					
LE4.3	+1.145	+1.67			+1,176 (M)
					+482 (J)
					+744 (D)
Rappahannock River					
TF3.3		+0.50			+429 (J)
					+522 (S)
RET3.1	+1.260			+1.8	+299 (J)
					+533 (D)
LE3.2					
Mainstem of Bay					
CB5.4					
CB6.1	+0.400	+0.50			+355 (M)
CB6.4		+0.86		−3.7	+744 (J)
					+410 (S)
					+473 (D)
CB7.3E	+0.687	+0.86			+1,487 (M)
					+1,614 (J)
					+625 (S)
					+849 (D)
CB8.1		+1.00			+1,045 (J)
					+315 (S)

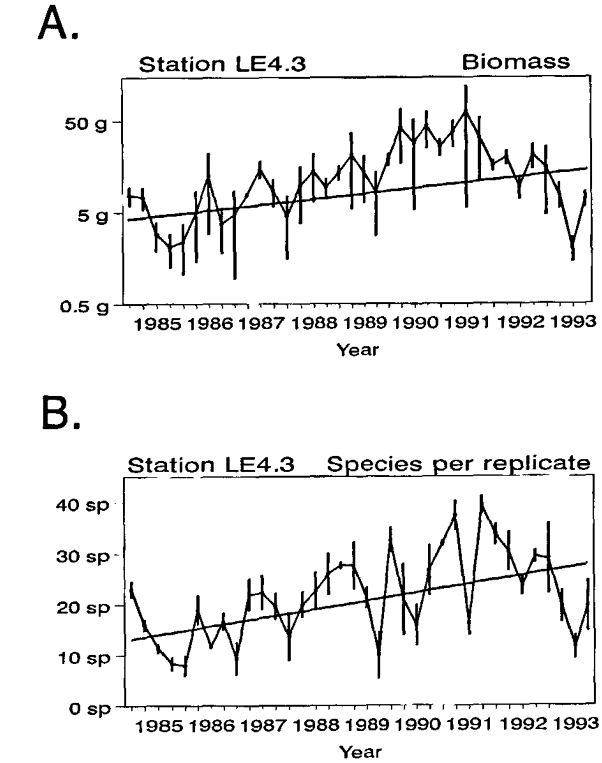

Figure 2

Trends representative of improving conditions for the benthos at Station LE4.3 of the York River. A. Biomass in g.m^{-2}. B. Species richness in species per replicate.

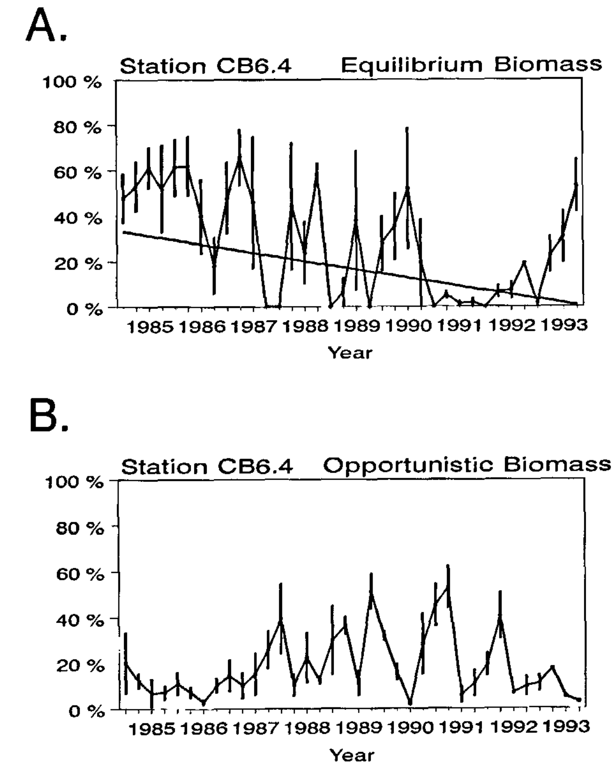

Figure 3

Trends representative of deteriorating conditions for the benthos at Station CB6.4 of the Mainstem of the Bay. A. Equilibrium Biomass as a percentage of community biomass. B. Opportunistic biomass as a percentage of community biomass.

with the expectation of deteriorating conditions for the benthos-decreasing composition of equilibrium species (Fig. 3*a*) and increasing composition of opportunistic species (Fig. 3*b*). However, through the nine year period (1985-1993) the previously significant increase in opportunistic biomass composition through 1991 was no longer significant and the negative slope of equilibrium biomass composition declined from −7.1 % (through 1991, Dauer and Alden, 1995) to −5.4 % (through 1992, Dauer, 1995) and finally to −3.7 % in this study. The increase in equilibrium biomass composition during 1993 was due to increases in the biomass of the polychaete species *Chaetopterus variopedatus* and *Macroclymene zonalis* which have been previously classified as equilibrium species (Dauer, 1991, 1993; Dauer *et al.*, 1992).

DISCUSSION

Interpretation of the ecological significance of trends in macrobenthic communities of the Chesapeake Bay is dependent upon the expected relationship between 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 and Rosenberg, 1978; Rhoads *et al.*, 1978; Gray, 1979; Rhoads and Boyer, 1982; Warwick, 1986; Dauer, 1993; Dauer *et al.*, 1993). Intermediate or moderate levels of organic enrichment may result in benthic communities with values for species richness, abundance of individuals, and biomass that are higher than values for benthic communities exposed to both high and low levels of organic enrichment (Beukema, 1991; Pearson and Rosenberg, 1978; Dauer and Conner, 1980; Ferraro *et al.*, 1991; Fallesen, 1992). Therefore, trends in species richness, abundance of individuals and biomass must be cautiously interpreted (Dauer and Alden, 1995) for eutrophication related effects. Expected patterns of community structure related to intermediate levels of sediment contamination are not well understood (Scott, 1989).

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 (Pearson and Rosenberg, 1978; Warwick, 1986). Consistent with these observations, trends in opportunistic species and equilibrium species composition of the benthic community are considered to be the best indicators of the ecological significance of the observed trends (Dauer and Alden, 1995). Improving conditions for the benthos should be accompanied by either 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 either a negative slope in equilibrium biomass composition and/or a positive slope for opportunistic biomass composition. However, functional group variables should not be used exclusively. In order to maximize the statistical robustness of decisions concerning improving versus deteriorating conditions, multiple variables, methods, or analyses with different assumptions should be used (Green, 1979; Dauer, 1993).

Long-term trends in macrobenthic communities in the North Sea, Wadden Sea and the Skagerrak have indicated increased levels of benthic community abundance and biomass associated with moderate levels of eutrophication (Austen *et al.*, 1991; Beukema, 1989, 1991, 1992; Beukema and Cadée, 1986; Beukema and Essink, 1986; Rachor, 1990). The studies of Beukema (1991, 1992) from 1970 through 1990 of the tidal flats of the western Wadden Sea indicate the following changes in the macrobenthic community associated with eutrohpication: (1) doubling of community biomass, (2) more than doubling of community abundance, and (3) compositional changes in feeding groups. All feeding groups (deposit feeders, suspension feeders, and carnivores) increased in absolute numbers but in terms of relative amounts deposit feeders increased, carnivores decreased and suspension feeders were unchanged. Eutrophication in the western Wadden Sea was characterized by (1) increases in primary productivity from levels of 150 gC m^{-2} yr^{-1} from 1970-1979 to 300 gC m^{-2} yr^{-1} after 1980 (Beukema 1991) and (2) increases of chlorophyll a concentrations from less than 5 mg m^{-3} ($\mu g l^{-1}$) from 1970-1979 to concentrations of 8-15 mg m^{-3} (μg l^{-1}) after 1980. These levels of eutrophication are comparable to that of the lower Chesapeake Bay where rates of primary productivity for the period of 1989-1994 ranged from 199 to 409 gC m^{-2} yr^{-1} and chlorophyll a values for the period of 1989-1991 ranged from 4.4-31.1 mg m^{-3} ($\mu g l^{-1}$) (Marshall and Nesius, 1993, 1996).

Based upon the expectations discussed above, the data in Table 1 indicate improving conditions for some regions of the James, York and Rappahannock rivers and deteriorating conditions for the benthos in one region of the mainstem of Chesapeake Bay (CB6.4). Previously, Dauer and Alden (1995) were able to inferentially relate trends in water quality to trends in the benthos in an ecologically meaningful manner. Specifically, they reported declines in the magnitude or reversal in direction in the slopes of nutrients and chlorophyll concentrations in the James and York rivers while measures of eutrophication continued to increase in the lower Rappahannock River. In the mainstem of the Chesapeake Bay, Dauer and Alden (1995) reported that water quality conditions continued to deteriorate with increasing nitrogen concentrations, seasonally increasing chlorophyll concentrations and decreasing bottom water oxygen concentrations including the region containing station CB6.4. Although no trends were detected for station LE3.2 in the lower Rappahannock River or for station CB5.4 in the mainstem of the bay, these stations have highly depressed macrobenthic communities due to summer low dissolved oxygen events (Dauer *et al.*, 1992; Llanso, 1992) and some depths become azoic (Smith and

Table 2

Comparison of trend analyses for the five year period from 1985-1989 – designated as 1989, the seven year period from 1985-1991 – designated as 1991, the eight year period 1985-1992 – designated as 1992, the nine year period from 1985-1993 – designated as 1993. For the five year period there were significant station-season interactions for species richness, opportunistic biomass and abundance, for the other periods only abundance had a significant station-season interaction. Numbers indicate the total trends in each tributary and in parentheses the sign of the slopes.

Tributary	Community Biomass	Species Richness	Opportunistic Biomass	Equilibrium Biomass	Abudance
James River					
1989	1 (+)	1 (+)	1 (–)		1 (+)
1991	3 (+)	3 (+)	1 (–)	1 (+)	5 (+)
1992	2 (+)	3 (+)	1 (–)	1 (+)	7 (+)
1993	2 (+)	2 (+)	1 (–)	1 (+)	8 (+)
York River					
1989	3 (+)	3 (+)	3 (–)	1 (+)	3 (+)
1991	2 (+)	2 (+)	1 (–)	1 (+)	5 (+)
1992	2 (+)	2 (+)	1 (–)		7 (+)
1993	2 (+)	2 (+)	1 (–)		4 (+), 1 (–)
Rappahannock River					
1989	1 (+)				
1991			1 (+)	1 (–)	3 (+)
1992	1 (+)	2 (+)	1 (+)	1 (+)	5 (+)
1993	1 (+)	1 (+)		1 (+)	4 (+)
Mainstem of Bay					
1989	1 (–)	1 (–)	2 (+)	2 (–)	1 (+)
1991		1 (+)	3 (+)	1 (–)	4 (+)
1992	2 (+)	3 (+)	3 (+)	1 (–)	6 (+)
1993	2 (+)	4 (+)		1 (–)	10 (+)

Dauer 1995). No trends were detected for the two stations in the Southern Branch of the Elizabeth River (SBE2, SBE5). These stations also have benthic communities characterized by very low levels of species richness, abundance and biomass and by dominance of opportunistic species (Dauer, 1993, Dauer *et al.*, 1993). Although new inputs of contaminants are presently being reduced or eliminated in the Elizabeth River, levels of heavy metals and synthetic organic compounds in the sediment are unlikely to decrease in the near future.

Previously Dauer (1991) reported trends in the macrobenthic communities of the Chesapeake Bay for the five year period 1985-1989, Dauer and Alden (1995) reported trends for the seven year period 1985-1991, Dauer (1995) reported trends for the eight year period 1985-1992 and this study reports trends for the nine year period 198-1993. Table 2 summarizes the comparisons between these studies. The total number of significant trends increased from 25 (through 1989), to 36 (through 1991), to 51 (through 1992), and finally to 48 (through 1993 in this study). The conclusions of this study of improving conditions for the benthos of the James, York and Rappahannock rivers and deteriorating conditions for the benthos of the mainstem of Chesapeake Bay are consistent with the results of Dauer (1991, 1995) and Dauer and Alden (1995). For the James and York rivers trends in community biomass, species richness, equilibrium biomass and abundance had positive slopes while opportunistic biomass had negative slopes in each analysis. For the Rappahannock River and the mainstem of the bay there was a mixture or trends indicative of either improving and deteriorating conditions. Trends indicative of deteriorating conditions were associated with stations affected by summer low dissolved oxygen events.

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REFERENCES

Alden R.W. III, J.C. Seibel, C.M. Jones (1990). *Analysis of the Chesapeake Bay program monitoring design for detecting water quality and living resources trends.* Final report to the Virginia State Water Control Board. Applied Marine Research Laboratory Report No. 747.

Austen M.C., J.B. Buchanan, H.G. Hunt, A.B. Josefson, M.A. Kendall (1991). Comparison of long-term trends in benthic and pelagic communities of the North Sea. *J. Mar. Biol. Ass. U.K.* **71**, 179-190.

Beukema J.J. (1989). Long-term changes in macrozoobenthic abundance on the tidal flats of the western part of the Dutch Wadden Sea. *Helgoländer Meeresunters.* **43**, 405-415.

Beukema J.J. (1991). Changes in the composition of bottom fauna of a tidal-flat area during a period of eutrophication. *Mar. Biol.* **111**, 293-301.

Beukema J.J. (1992). Long-term and recent changes in the benthic macrofauna living on tidal flats in the western part of the Wadden Sea. In: *Present and future conservation of the Wadden Sea. Proceedings of the 7th International Wadden Sea Symposium,* ed. by N. Dankers, C.J. Smit, M. Scholl, Netherlands Institute for Sea Research, Publication Series No. 20, Texel, The Netherlands, p. 135-141.

Beukema J.J., G.C. Cadée (1986). Zoobenthos responses to eutrophication of the Dutch Wadden Sea. *Ophelia* **26**, 55-64.

Beukema J.J., K. Essink (1986). Common patterns in the fluctuations of macrobenthic species living at different places on tidal flats in the Wadden Sea. *Hydrobiologia* **142**, 199-207.

Boesch D.F. (1977). A new look at the zonation of benthos along the estuarine gradient. In: *Ecology of marine benthos,* ed. by B.C. Coull, Univ. of South Carolina Press, Columbia, 245-266.

Buchanan J.B., J.J. Moore (1986). Long-term studies at a benthic station off the coast of Northumberland. *Hydrobiologia* **142**, 121-127.

Dauer D.M. (1991). Long-term trends in the benthos of the lower Chesapeake Bay. In: *New perspectives in the Chesapeake System.* A research and management partnership, ed. by J. A. Mihursky, A. Chaney. Chesapeake Research Consortium, 527-536.

Dauer D.M. (1993). Biological criteria, environmental health and estuarine macrobenthic community structure. *Mar. Pollut. Bull.* **26**, 249-257.

Dauer D.M. (1995). Long-term trends in the lower Chesapeake Bay 1985-1992: IV. Benthos. In: *Toward a sustainable coastal watershed: The Chesapeake Experiment.* P. Hill, S. Nelson eds. Chesapeake Research Consortium Publication **149**, p. 430-440.

Dauer D.M., R.W. Alden III. (1995). Long-term trends in the macrobenthos and water quality of the lower Chesapeake Bay (1985-1991). *Mar. Pollut. Bull.* **30**, 840-850.

Dauer D.M., W.G. Conner (1980). Effects of moderate sewage input on benthic polychaete populations. *Estuar. Coast. Mar. Sci.* **10**, 335-346.

Dauer D.M., R.M. Ewing, J.A. Ranasinghe, A.J. Rodi Jr. (1989). *Macrobenthic communities of the lower Chesapeake Bay.* Chesapeake Bay Program. Final Report the Virginia Water Control Board. 296 p.

Dauer D.M., M.W. Luckenbach, A.J. Rodi Jr. (1993). Abundance biomass comparison (ABC method): effects of an estuarine gradient, anoxic/hypoxic events and contaminated sediments. *Mar. Biol.* **116**, 507-518.

Dauer D.M., A.J. Rodi Jr., J.A. Ranasinghe (1992). Effects of low dissolved oxygen events on the macrobenthos of the lower Chesapeake Bay. *Estuaries* **15**, 384-391.

Fallesen G. (1992). How sewage discharge, terrestrial run-off and oxygen deficiencies affect the bottom fauna in rhus Bay, Denmark. In: *Marine eutrophication and population dynamics,* ed. by C. Giuseppe, I. Ferrari, V.U. Ceccherelli, R. Rossi, 25th European Marine Biology Symposium. Olsen and Olsen, Fredensborg, 29-33.

Ferraro S.P., R.C. Swartz, F.A. Cole, D.W. Schults (1991). Temporal changes in the benthos along a pollution gradient: discriminating the effects of natural phenomena from sewage-industrial wastewater effects. *Estuar. Coast. Shelf Sci.* **33**, 383-407.

Gilbert R.O. (1987). *Statistical methods for environmental pollution monitoring.* Van Nostrand Reinhold Co., New York, 320 p.

Gray J.S. (1979). Pollution-induced changes in populations. *Phil. Trans. R. Soc. Lond. Ser.* B, **286**, 545-561.

Green R.H. (1979). *Sampling design and statistical methods for environmental biologists.* Wiley-Interscience, New York, 257 p.

Hirsch R.M., J.R. Slack, R.A. Smith (1982). Techniques of trend analysis for monthly water quality data. *Wat. Resour. Res.* **18**, 107-121.

Holland A.F., N.K. Mountford, J.A. Mihursky (1977). Temporal variation in upper bay mesohaline benthic communities: I. The 9-m mud habitat. *Ches. Sci.* **18**, 370-378.

Holland A.F., A.T. Shaughnessy, H. Hiegel (1987). Long-term variation in mesohaline Chesapeake Bay macrobenthos: spatial and temporal patterns. *Estuaries* **10**, 227-245.

Kuo A.Y., B.J. Neilson (1987). Hypoxia and salinity in Virginia estuaries. *Estuaries* **10**, 277-283.

Llanso R.J. (1992). Effects of hypoxia on estuarine benthos: the lower Rappahannock River (Chesapeake Bay), a case study. *Estuar. Coast. Shelf Sci.* **35**, 491-515.

Marshall H.G., K.K. Nesius (1993). Seasonal relationships between phytoplankton composition, abundance, and primary productivity in three tidal rivers of the lower Chesapeake Bay. *Journal of Elisha Mitchell Scientific Society* **109**, 141-151.

Marshall H.G., K.K. Nesius (1996). Phytoplankton compostion in relation to primary production in Chesapeake Bay. *Mar. Biol.* **125**, 611-617.

McCall P.L. (1977). Community patterns and adaptive strategies of the infaunal benthos of Long Island Sound. *J. Mar. Res.* **35**, 221-266.

Officer C.B., R.B. Biggs, J.L. Taft,. L.E. Cronin, M.A. Tyler, W.R. Boyer (1984). Chesapeake Bay anoxia: origin, development and significance. *Science* **223**, 22-27.

Pearson T.H., G. Duncan, J. Nuttall (1986). Long term changes in the benthic communities of Loch Linnhe and Loch Eil (Scotland). *Hydrobiologia* **142**, 113-119.

Pearson, T.H., R. Rosenberg (1978). Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanogr. Mar. Biol. Ann. Rev.* **16**, 229-311.

Pihl L., S.P. Baden, R.J. Diaz (1991). Effects of periodic hypoxia on distribution of demersal fish and crustaceans. *Mar. Biol.* **108**, 349-360.

Rachor E. (1990). Changes in sublittoral zoobenthos in the German Bight with regard to eutrophication. *Nether. J. Sea Res.* **25**, 209-214.

Rhoads D.C., L.F. Boyer (1982). The effects of marine benthos on physical properties of sediments: a successional perspective. In: Animal-sediment relations, ed. by P.L. McCall, M.J.S. Tevesz, Plenum Press, New York, 3-52.

Rhoads D.C., P.L. McCall, J.Y. Yingst (1978). Disturbance and production on the estuarine seafloor. *Amer. Scient.* **66**, 577-586.

Scott K.J. (1989). Effects of contaminated sediments on marine benthic biota and communities. In: *Contaminated marine sediments-assessment and remediation,* (National Research Council), National Academy Press, Washington, D.C., 132-154.

Sen P.K. (1968). On a class of aligned rank order tests in two-way layouts. *Ann. Math. Stat.* **39**, 1115-1124.

Smith D.E., M. Leffler, G. Mackiernan (1992). *Oxygen dynamics in the Chesapeake Bay. A synthesis of recent research.* Maryland Sea Grant College, College Park, Maryland, 234 p.

Smith M.F., D.M. Dauer (1995). Eutrophication and macrobenthic communities of the lower Chesapeake Bay. Acute effects of low dissolved oxygen in the Rappahannock River. In: *Toward a sustainable coastal watershed: The Chesapeake Experiment.* Hill P., S. Nelson eds. Chesapeake Research Consortium Publication **149**, p. 76-84.

Swartz R.C., H. Lee II. (1980). Biological processes affecting the distribution of pollutants in marine sediments. Part I. Accumulation, trophic transfer, biodegradation and migration, in: *Contaminants and sediments,* Vol. 2, Analysis, Chemistry, Biology, ed. by R.A. Baker, Ann Arbor Science, Ann Arbor, Michigan, 533-554.

Taft J.L., W.R. Taylor, E.O. Hartwig, R. Loftus (1980). Seasonal oxygen depletion in Chesapeake Bay. *Estuaries* **3**, 242-247.

Van Belle G., J.P. Hughes (1984). Nonparametric tests for trend in water quality. *Wat. Resour. Res.* **20**, 127-136.

Warwick R.M. (1986). A new method for detecting pollution effects on marine macrobenthic communities. *Mar. Biol.* **92**, 557-562.