Journal of Experimental Marine Biology and Ecology
285-286 (2003) 371–381

Journal of
EXPERIMENTAL
MARINE BIOLOGY
AND ECOLOGY

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# A comparison of two methods for estimating the status of benthic habitat quality in the Virginia Chesapeake Bay

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Received 7 June 2002; received in revised form 31 August 2002; accepted 13 September 2002

**Abstract**

Macrobenthic communities in Chesapeake Bay, USA, have been intensively monitored since 1985. In 1996, the monitoring was expanded to include summertime stratified random sampling to produce unbiased estimators of community metrics that could be used to assess system wide trends in benthic habitat quality. From 1996 to 1998, two index approaches to assessing benthic habitat quality were used in the Virginia portion of Chesapeake Bay. One method relied on grab samples for calculation of the benthic index of biotic integrity (BIBI) based on macrobenthic community composition data. The other method used sediment profile camera images for calculation of the organism–sediment index (OSI) from image-derived data. On an annual basis, the mean for each of the indices were similar from year to year, indicating that the properties or processes that regulate benthic habitat quality were likely similar from 1996 to 1998. There were significant differences in the correspondence of the macrofaunal-based and image-based indices to classify a particular station as having stressed or good habitat quality. While the overall relationship between the scoring of each index for a station was significantly positive (1.4 odds ratio), when the BIBI indicated poor conditions existed at a station, the OSI tended to indicate good habitat quality at the station. This pattern was consistent with the hypothesis that benthic habitat quality (measured by the OSI) would improve before biotic integrity (measured by the BIBI). A high BIBI with low OSI, representing the opposite hypothesis, would be unlikely and rarely occurred. The formulation of macrofaunal-based BIBI and image-based OSI emphasized different aspects of the benthos–habitat relationship. The BIBI was community structure-oriented with an emphasis on species identity and richness. The OSI was process-oriented in that the images recorded the end products of biological and physical

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PII: S0022-0981(02)00538-5

processes that structure the benthos. Indices such as BIBI and OSI that integrate structural and functional aspects of benthos hold promise as measures of benthic habitat quality.


*Keywords:* Biotic indices; Biotic integrity; Chesapeake Bay; Habitat quality; Macrobenthos; Sediment profile imaging

## 1. Introduction

Central to many issues facing environmental managers is estimating habitat quality or the ability of a habitat to support various living resources, both commercial and noncommercial species. Among the first quantitative or numerically scored indices of habitat quality for aquatic systems was that of Karr et al. (1986), who develop an index for stream fishes. Their index of biotic integrity (IBI) has been widely applied and spawned a series of indices that eventually extended to freshwater stream invertebrates (Kerans and Karr, 1994) and then to estuarine invertebrates (Weisberg et al., 1997; Van Dolah et al., 1999). All these indices rely on a combination of data from samples collected from the target populations and water quality. The development of remote sensing methods for the

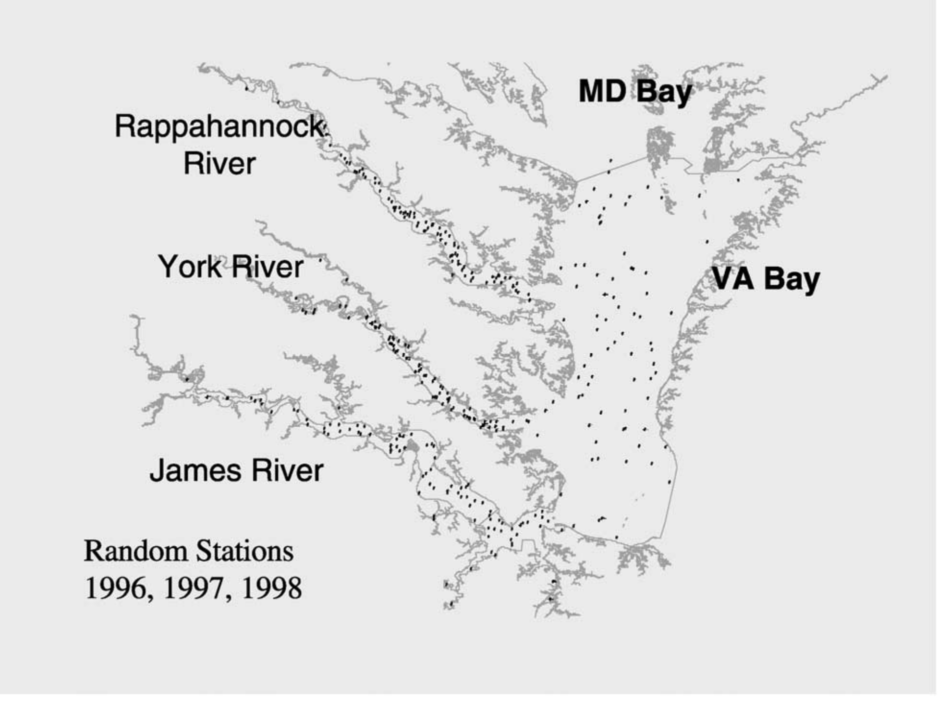


Fig. 1. Location of randomly selected monitoring stations in the Virginia portion of Chesapeake Bay from 1996 to 1998.

benthos based on sediment profile cameras (Rhoads and Cande, 1971) lead to a new type of index based on data derived from sediment profile images. The organism–sediment index (OSI) of Rhoads and Germano (1986) and benthic habitat quality index (BHQ) of Nilsson and Rosenberg (1997) were developed and applied to assessing benthic habitat quality based only on sediment profile images. This diversity of approaches and indices for assessing habitat quality points to two key factors in their development: (1) the disciplinary and methodological preferences of those developing the indices, and (2) regional factors that affect the value of each index and limit its global application (for example, Smogor and Angermeier, 2001).

In 1985, a monitoring program was started in Chesapeake Bay by the US Environmental Protection Agency to assess the quality of benthic habitats. For the first 10 years, monitoring in was performed at fixed station locations (Dauer, 1997). In 1996, summertime stratified random sampling was incorporated into the monitoring of the Virginia portion of the bay with 25 stations in each of three major tributaries (Rappahannock, York, and James Rivers) and Bay mainstem (Fig. 1). The addition of randomness to the monitoring program produced unbiased estimators of community metrics that could be used to assess system wide trends in benthic habitat quality (Alden et al., 1997). For a 3-

Table 1
Metrics used in the calculation of the benthic index of biotic integrity (BIBI) and organism–sediment index (OSI)

| BIBI | OSI |
|---|---|
| Species diversity $H'$ | Depth of apparent color RPD layer: Scored 0 for 0 RPD to 6 for >3.8 cm |
| Total abundance | Estimated successional stage: Scored −4 for azoic conditions to 6 for Stage III |
| Total biomass | Presence of gas voids in sediment: Scored −2 |
| % Abundance of pollution-indicative taxa | Apparent presence of low dissolved oxygen: Scored −4 |
| % Abundance of pollution-sensitive taxa | |
| % Biomass of pollution-sensitive taxa | |
| % Biomass >5 cm below sediment–water interface | |

Each metric gets a score of:
5: >50th percentile of reference sites
3: 5th to 50th percentile
1: <5th percentile

Range of index values for assessing Chesapeake Bay benthic habitats

| Category | BIBI | OSI |
|---|---|---|
| Highest quality habitat | 5 | 6 to 11 |
| Good | 3.0 to 4.9 | 3 to 5.9 |
| Marginally stressed | 2.7 to 2.9 | −1 to 2.9 |
| Stressed | 2.0 to 2.6 | −5 to −0.9 |
| Severely stressed | <2 | <−5 |

year period, from 1996 to 1998, two methods of assessing benthic habitat quality were used. One method relied on grab samples for calculation of the benthic index of biotic integrity (BIBI) based on macrobenthic community composition data and developed for use in Chesapeake Bay by Weisberg et al. (1997). The other method used sediment profile images for calculation of the OSI (Rhoads and Germano, 1986) and was developed for use mainly in cold-temperate estuarine systems. The two indices provide a means for scaling various parameters and either summing or averaging values to arrive at a score that can then be used to assess benthic habitat quality. The BIBI is based on seven community structure and function metrics. The OSI is based on estimates of benthic successional stage and RPD layer depth, and one water quality metric (Table 1).

The objective of this study was to compare the two different methodological approaches for estimation of benthic habitat quality and identify those aspects of macrobenthic community structure and function, and physical habitat characteristics to which the indices are most sensitive.

## 2. Methods

From 1996 to 1998, both grab samples and sediment profile images were collected at randomly selected stations in the Virginia portion of Chesapeake Bay within the period of 15 July to 30 September (Fig. 1). Indexing the indices to summertime conditions served two purposes: (1) it allowed direct comparisons between years, and (2) it provided a measure of habitat quality when major stress factors, such as temperature and low dissolved oxygen, were at their peak. Details of sample processing protocol for the grabs can be found in Dauer (1997). In summary, macrofaunal samples were collected using a Young modified Van Veen grab (surface area of 440 $cm^2$) and sieved on a 0.5-mm screen. A Hulcher sediment profile camera was used to collect in situ sediment profile images. Details of image processing methods can be found in Diaz and Schaffner (1988). Twenty-five stations were randomly allocated to each of four systems (James River, York River, Rappahannock River, and the mainstem of Virginia portion of Chesapeake Bay). Each year, a new set of random sampling sites within each system was selected.

Thresholds for the selected metrics that composed the BIBI (Table 1) were based on the distribution of values for the metric at sites scattered around the Chesapeake Bay that were considered to represent reference conditions for the macrobenthos. Data from these sites were used to determine the cumulative distribution of each metric. The IBI approach involves scoring each metric as 5, 3, or 1, depending on whether its value at a site approximates, deviates slightly, or deviates greatly from conditions at reference sites (Karr et al., 1986). Threshold values were established at the 5th and 50th percentile values for reference sites. For each metric, values below the 5th percentile were scored as 1; between the 5th and 50th percentiles scored as 3; and values above the 50th percentile scored as 5. The final index value for a site was computed by averaging the scores of the individual metrics. The BIBI ranges from 1 to 5. Index values $< 3.0$ were considered to indicate the presence of a stressed macrobenthos because, on average, the metrics are less than values at the poorest reference sites (Weisberg et al., 1997). A BIBI score from 2.7 to 2.9 was considered to be marginally stressed, 2.0 to 2.6 stressed, and $< 2.0$ severely stressed. A

BIBI score of 3.0 or higher indicated that the macrobenthos did not differ from reference conditions and represented good benthic habitat conditions.

Rhoads and Germano (1986) developed the organism–sediment index (OSI), from data provided by sediment profile images, to characterize benthic habitat quality. The OSI defines quality of benthic habitats by evaluating images for depth of the apparent color RPD layer, successional stage of macrofauna, the presence of gas bubbles in the sediment (an indication of high rates of methanogenisis), and the presence of reduced sediment at the sediment–water interface that would indicate current or recent low dissolved oxygen conditions (Table 1). The OSI ranges from $-10$, poorest quality habitats, to 11, highest quality habitats. In northeastern estuarine and coastal ecosystems, which represent cold-temperate and boreal conditions where the OSI was developed, values >6 were associated with higher quality habitats with well-developed macrofaunal communities. For use in Chesapeake Bay, which is warm-temperate, the critical value of the OSI index that delineates stressed/nonstressed benthic habitat was adjusted to reflect latitudinal effects that narrow the range of OSI from north to south (Diaz, unpublished data). Based on comparison of sediment profile image parameters with the general developmental levels of macrobenthos at the fixed monitoring station in the Chesapeake system, also sampled from 1996 to 1998, we found that an OSI value of 3 was representative of good benthic habitat quality. Macrofaunal communities in most of the Chesapeake system do not reach the higher end of the successional scale, Stage III, and are not capable of producing the deeper RPD layers needed to obtain highest possible OSI values. Thus for scaling the OSI to assess Chesapeake Bay benthic habitat quality, values $< -5.0$ were considered to be severely stressed, $-5.0$ to $-0.9$ stressed, $-1.0$ to 2.9 marginally stressed, and 3.0 or greater to be good habitat quality.

For each station, the BIBI was calculated from the macrofauna data following the methods of Weisberg et al. (1997) and the OSI calculated from the sediment profile images as described by Rhoads and Germano (1986). The metrics used are described in Table 1. Analysis of variance was used to test for differences between years and systems for all indices. Normality was checked with the Shapiro–Wilk test and homogeneity of variance with Bartlett's test (Zar, 1999). The ability of the indices to consistently classify a station's habitat quality as either stressed, marginal, or good was evaluated using a symmetry model, which measures association in cross-classifications having ordered categories by testing a more specific hypothesis of independence that measure departure of data point from the table's diagonal. The distance between categories was considered to be equal and was set to unit-spaced scores, which generated a uniform association model (Agresti, 1990). This model compared the ability of the indices to jointly classify the benthic habitat conditions at a station. If the two indices agreed on benthic habitat quality, then the cross-classification of stations would be aliened on the diagonal of the classification table. If the metric disagreed on the habitat conditions, more of the stations would be found off the diagonal and toward the corners of the classification table.

## 3. Results

Of the 300 random samples collected from 1996 to 1998, 230 had calculations for indices based on both benthic grab and sediment profile camera sampling methods. The

70 stations with missing values for the sediment profile image indices (23% of the total) were excluded from comparisons. Overall, there were 56 stations from the Rappahannock River, 51 from the York River, 60 from the James River, and 63 from the Bay mainstem (Table 2).

On average, the BIBI was higher in 1996 (ANOVA, $df = 2$, $p = 0.031$) relative to 1997 and 1998 with highest BIBI values in James River and Chesapeake mainstem (Table 2). However, there was an interaction between year and system (year × system, $df = 3$, $p = 0.009$). The benthos in the Rappahannock and York Rivers responded differently through time than the other two systems with little change in the BIBI. When averaged for the three year period by system, the BIBI indicated that benthic habitat quality was marginally stressed in James River and Chesapeake mainstem, 2.8 (S.E. 0.10) and 2.8 (S.E. 0.08), respectively, and stressed in the Rappahannock and York Rivers, 2.4 (S.E. 0.06) and 2.5 (S.E. 0.08), respectively. The percentage of stations that were classified as having stressed macrobenthos, a BIBI of at least 3, was 48% for the James River, 52% for the Bay mainstem, 71% for the York River, and 84% for the Rappahannock River (Table 3).

On average, the OSI was similar from year to year (ANOVA, $df = 2$, $p = 0.966$) but there was a significant two-way interaction of year and system (year × system, $df = 3$, $p = < 0.001$) that was related primarily to temporal differences in OSI. In 1996, higher

Table 2
Summary of benthic indices by year and system

| Year | *N* | BIBI | | | | OSI | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | S.E. | Min | Max | Mean | S.E. | Min | Max |
| *Rappahannock River* | | | | | | | | | |
| 96 | 17 | 2.4 | 0.13 | 1.8 | 3.7 | 1.9 | 0.87 | −7 | 6 |
| 97 | 17 | 2.5 | 0.10 | 1.7 | 3.3 | 2.9 | 0.37 | 2 | 8 |
| 98 | 22 | 2.4 | 0.09 | 1.7 | 3.4 | 2.8 | 0.76 | −9 | 7 |
| All | 56 | 2.4 | 0.06 | 1.7 | 3.7 | 2.6 | 0.41 | −9 | 8 |
| *York River* | | | | | | | | | |
| 96 | 15 | 2.5 | 0.19 | 1.4 | 4.0 | 1.1 | 1.18 | −9 | 7 |
| 97 | 19 | 2.4 | 0.14 | 1.3 | 3.4 | 3.6 | 0.45 | 0 | 7 |
| 98 | 17 | 2.6 | 0.12 | 1.7 | 3.3 | 3.1 | 0.71 | −7 | 6 |
| All | 51 | 2.5 | 0.08 | 1.4 | 4.0 | 2.7 | 0.47 | −9 | 7 |
| *James River* | | | | | | | | | |
| 96 | 20 | 3.0 | 0.17 | 2.0 | 4.5 | 3.6 | 0.49 | 0 | 8 |
| 97 | 18 | 2.4 | 0.19 | 1.3 | 3.8 | 3.1 | 0.23 | 1 | 5 |
| 98 | 22 | 2.8 | 0.15 | 1.8 | 3.8 | 3.1 | 0.47 | 0 | 8 |
| All | 60 | 2.8 | 0.10 | 1.3 | 4.5 | 3.3 | 0.24 | 0 | 8 |
| *Chesapeake Bay, Virginia* | | | | | | | | | |
| 96 | 21 | 3.1 | 0.12 | 2.0 | 4.0 | 6.0 | 0.48 | 3 | 10 |
| 97 | 20 | 2.7 | 0.10 | 2.0 | 3.7 | 2.5 | 0.33 | −3 | 4 |
| 98 | 22 | 2.4 | 0.14 | 1.0 | 3.7 | 3.5 | 0.96 | −9 | 8 |
| All | 63 | 2.8 | 0.08 | 1.0 | 4.0 | 4.0 | 0.42 | −9 | 10 |

Table 3
Assessment of benthic habitats for the Virginia portion of Chesapeake Bay based on the 230 stations used in the comparison of BIBI and OSI indices from 1996 to 1998

| System | BIBI | | OSI | | Principal stressor |
|---|---|---|---|---|---|
| | Stressed | Good | Stressed | Good | |
| Rappahannock River | 47 | 9 | 26 | 30 | annual hypoxia/anoxia |
| York River | 36 | 15 | 18 | 33 | sediment instability |
| James River | 29 | 31 | 23 | 37 | toxics |
| Chesapeake Bay, Virginia | 33 | 30 | 12 | 51 | annual hypoxia |

OSI values occurred in James River and Chesapeake mainstem and lower values in Rappahannock and York Rivers (Table 2). Averaged OSI between systems indicated that overall the benthic habitat quality was marginally stressed in the Rappahannock and York Rivers, 2.6 (S.E. 0.41) and 2.7 (S.E. 0.47), respectively, while the James River and Chesapeake mainstem had good habitat quality, 3.3 (S.E. 0.24) and 4.0 (S.E. 0.42), respectively. The percentage of stations that were considered stressed based on the OSI (a value $<3$) was lower than for the BIBI with the mainstem being 19%, the York River 35%, the James River 38%, and the Rappahannock 46% (Table 3).

While significantly different than zero, the correlation between the grab and image-based indices was low ($n=230$, $r=0.17$) and pointed to a discrepancy in the ability of the indices to concordantly measure some function of benthic habitat quality. While the indices approached the quantification of benthic quality in different ways, it appeared that they were not consistently giving the same answer for the same station. The uniform association models had a significant improvement fit over models of general independence particularly in the corners of the tables (Table 4). While the concordance of the indices was positive indicating that as one index increased so did the other, the local odds ratios of 1.4 was low (Table 4). The local odds ratio estimates the proportional increase in cell frequencies as the index category change by one level. The BIBI tended to underestimate benthic habitat quality or conversely that the OSI tended to overestimate habitat quality with the largest departures from uniform association occurring when the BIBI indicated good habitat quality. Observed frequencies were lower than expected for OSI categories of stressed and good, and higher than expected when marginally stressed (Table 4).

Table 4
Comparison of the BIBI and OSI for assessing benthic habitat

| | | OSI | | | | Model fit |
|---|---|---|---|---|---|---|
| | | Stressed | Marginal | Good | Total | |
| BIBI | Stressed | 9 (7.9) | 39 (40.7) | 70 (69.4) | 118 | $df=1$; $G^2(I\|U)=5.68$; |
| | Marginal | 1 (1.1) | 7 (7.7) | 19 (18.2) | 27 | $p=0.017$; |
| | Good | 1 (19.6) | 22 (1.1) | 62 (80.8) | 85 | local odds ratio = 1.4; |
| | Total | 11 | 68 | 151 | 230 | 95% CI = 1.1–1.8 |

Index levels for each category are in Table 1. Expected frequencies for uniform association model are given in parentheses.

## 4. Discussion

On an annual basis, the mean values for the BIBI and OSI were similar from year to year indicating that the properties or processes that regulate benthic habitat quality were similar from 1996 to 1998. Basically the BIBI indicated that values of key benthic community attributes, such as species diversity ($H'$) or biomass, did not change significantly over the 3-year period. Similarly, the OSI indicated that processes structuring benthic habitats, such as bioturbation, did not significantly change either.

The BIBI and OSI emphasize different aspects of the benthos–habitat relationships. The macrofaunal-based BIBI being derived from organism data is more a measure biotic integrity (in the sense of Karr et al., 1986). The community structure orientation of the BIBI emphasizes species identity and richness, which are thought to be intrinsically important features of the benthos. When community structure indices are high, it is assumed that benthic habitat quality is also high. The OSI derived from sediment profile image data on biological and physical sedimentary properties and processes is more a measures benthic habitat quality. The remote sensing nature sediment profile imaging makes the OSI a process-oriented index in that the images record the end products of biological and physical processes that structure sediments. When evidence of high levels of macrofaunal activity is present in the images, it is assumed that benthic habitat quality is good. Bioturbation levels and biogenic structures are directly related to macrofaunal successional stage and activity, in the sense of Odum (1969) and Zajac (2001), which are more an estimate of infaunal functional richness rather than community structure and integrative of biotic integrity.

While one would expect good biotic integrity to be associated with good habitat quality, the distribution of the indices between the tributaries and mainstem of the Virginia portion of Chesapeake Bay reflected basic differences in the theoretical basis of the indices and the prominent stressors in each of the systems. The BIBI and OSI appear to be most responsive to organic enrichment gradients as described by the basic benthic response model of Pearson and Rosenberg (1978) and long-term events such as sever annual hypoxia (Rosenberg et al., 2001). The BIBI also appears to be more sensitive to short-term stressors that reduce species diversity and total abundance than the OSI. The principal factors stressing the macrobenthos and degrading benthic habitat quality in the Rappahannock River are sever annual hypoxia and anoxia (Llansó, 1992) that produces strong gradient in both macrobenthic community composition and habitat quality (Diaz and Rosenberg, 1995). In the York River surface, sediment instability (Dellapenna et al., 2001) appears to be the primary stressor that keeps communities in early successional stages (Schaffner et al., 2001). In localized areas of the James River system, toxics are the primary stressor that reduce community structure and habitat quality (Hawthorne and Dauer, 1983; Diaz et al., 1993) with sediment instability being a more general stressor (Schaffner et al., 1987). Annual hypoxia stresses the Virginia bay mainstem north of the Rappahannock River (Dauer et al., 1992).

After a disturbance, such as a storm or hypoxic event, one might expect habitat quality to improve before biotic integrity if there was a time lag between recruitment necessary to restore biotic integrity. The primary difference in what each of the indices measured, biotic integrity vs. habitat quality, is summarize in Table 5. While the overall

Table 5
Association between indices of biotic integrity and habitat quality

| Biotic integrity (BIBI) | Habitat quality OSI | |
|---|---|---|
| | Low | High |
| Low | Strong relationship, 24% (56 stations) | May occur due to biotic factors, 39% (89) |
| High | Not likely, 10% (23) | Strong relationship, 27% (62) |

relationship between the scoring of each index was positive (significantly >1 odds ratio, Table 4) when the BIBI indicated stressed conditions for the macrobenthos, the OSI tended to indicate the presence of good benthic habitat. The combination of low BIBI with high OSI is more likely to occur because the imprint of biotic processes on sedimentary structure survives for varying periods of time after the organisms are removed (Diaz and Cutter, 2001). The combination of high BIBI with low OSI is not likely because higher levels of community structure and function required for a high BIBI could not occur without the presence of significant biogenic structure in the image-based indices. Only 1 of the 230 stations was in the category of good BIBI and stressed OSI (Table 4).

Spatial variability in community structure measures and sedimentary processes likely accounted for much of the mismatch between the indices. At all stages of community development, predation pressure would be a major factor in removing organisms and lowering of community structure and function measures used by the BIBI but leaving intact biogenic structure that would be recorded by the OSI. Poor or spatially variable recruitment would be another factor, as lack of recruits would tend to lower most BIBI metrics. A total of 70 stations were in the category of stressed BIBI and good OSI.

Indices such as BIBI and OSI that integrate structural and functional aspects of benthos hold promise as measures of benthic habitat quality. The emphasis on benthic indices is appropriate because central to the assessment of a system's viability or health is the quality of its benthic habitats and the communities they support. Processes that shape the biological and physical characteristics of the sediment–water interface determine much of the perceived health of estuarine and coastal system. Interactions and reactions at the sediment–water interface are of particular importance in regulating processes involving nutrient regeneration and remineralization (Boynton and Kemp, 1985), fate of toxicants (Olsen et al., 1982), development of hypoxia–anoxia (Diaz and Rosenberg, 1995), and sediment mixing (Schaffner et al., 1987). All of these processes directly influence the quality of the bottom to support living resources.

## Acknowledgements

The Commonwealth of Virginia, Department of Environmental Quality supported this work as part of the U.S. Environmental Protection Agency's Chesapeake Bay Program. We thank B. Rodi for collection and processing of grab samples, J. Randall for image processing, and our contract manager R. Hoffman for his support. This is contribution number 2510 of the Virginia Institute of Marine Science. **[RW]**

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